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THE MECHANICAL PROPERTIES OF INCONEL 718 SHEET

ALLOY AT 800°, 1000°, AND 1200° F

By T. M. Cullen and J. W. Freeman

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ABSTRACT

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An investigation has been conducted to evaluate the potential usefulness of Inconel 718 sheet material in the supersonic transport. Because of the likelihood that this superalloy would only see service in the hottest portions of the aircraft skin, the evaluation of its potential usefulness has been based on creep and rupture properties in the temperature range from 800° to 1200°F.

The results showed that the creep and rupture properties of the alloy were sensitive to the prior thermal history the alloy had received. In the cold worked and aged condition Inconel 718 sheet had very low creep and rupture strengths at 1200°F and poor notched specimen rupture properties at 1000°F. The alloy annealed at 1950°F and aged exhibited high creep and rupture strengths at temperatures up to 1200°F but low notched specimen rupture strengths at 1200°F. The material annealed at 1750°F and aged had excellent notched specimen rupture properties at 1200°F but relatively low creep and rupture strengths at this temperature.

Evaluation of the results from the viewpoint of the expected design criteria showed that the alloy annealed at 1750°F and aged offered the most potential for application in the supersonic transport. In this condition the alloy should be serviceable up to approximately 1150°F.



TABLE OF CONTENTS

	PAGE
INTRODUCTION	1
EXPERIMENTAL MATERIAL	2
EXPERIMENTAL PROCEDURES	3
Specimens	3
Unnotched specimens	3
Notched specimens	4
Creep and Rupture Tests	4
Tensile Tests	5
RESULTS	6
Cold Worked and Aged Condition	6
Tensile properties	6
Creep resistance	6
Rupture properties	6
Smooth specimen results	7
Notched specimen results	7
Discontinued tests	8
Annealed at 1750°F and Aged	9
Tensile properties	9
Creep strength	9
Rupture strength	9
Smooth specimen results	9
Notched specimen results	10
Interrupted tests	11
Annealed at 1950°F and Aged	12
Tensile properties	12
Creep resistance	12
Rupture properties	12
Smooth specimen results	12
Notched specimen results	13
Interrupted tests	13

TABLE OF CONTENTS (continued)

	PAGE
DISCUSSION	14
Influence of Heat Treatment on Strength	14
Rupture strength	14
Creep resistance	15
Notched specimen properties	16
Applicability of Results	17
CONCLUSIONS	18
REFERENCES	19

LIST OF TABLES

TABLE		PAGE
I	Tensile Results from Smooth and Notched Specimens in Cold Worked and Aged Condition	20
II	Creep and Rupture Data from Smooth Specimens in Cold Worked and Aged Condition	21
III	Notched Specimen Rupture Results from Alloy in Cold Worked and Aged Condition	22
IV	Rupture Test Results from Sharp Edge-Notched Specimens in Cold Worked and Aged Condition	23
V	Influence of 800°F Stressed Exposure on Smooth Specimen Tensile Properties	24
VI	Influence of Stressed Exposure on Notched Specimen Strength	25
VII	Tensile Results from Smooth and Notched Specimens Annealed at 1750°F and Aged	26
VIII	Creep and Rupture Data from Smooth Specimens Annealed at 1750°F and Aged	27
IX	Notched Rupture Results from Specimens Annealed at 1750°F and Aged	28
X	Rupture Test Results from Sharp Edge-Notched Specimens Annealed at 1750°F and Aged	29
XI	Comparison of 1000-Hour Rupture Strengths.	30
XII	Tensile Test Results from Smooth and Notched Specimens Annealed at 1950°F and Aged	31

LIST OF TABLES (continued)

TABLE		PAGE
XIII	Creep and Rupture Results from Smooth Specimens Annealed at 1950°F and Aged . . .	32
XIV	Notched Specimen Rupture Properties of Inconel 718 Alloy Annealed at 1950°F and Aged	33
XV	Rupture Test Results from Sharp Edge-Notched Specimens Annealed at 1950°F and Aged	34

LIST OF FIGURES

FIGURE	PAGE
Types of Test Specimens	35
Stress versus minimum creep rate behavior of Inconel 718 in the cold worked and aged condition	36
Stress-rupture time curves from smooth specimens of Inconel 718 in the cold worked and aged condition	37
Stress-rupture time curves from edge-notched specimens ($K_t = 6.0$) of Inconel 718 in the cold worked and aged condition	38
Stress versus rupture time behavior of ASTM sharp edge-notched specimens of Inconel 718 in the cold worked and aged condition	39
Stress versus minimum creep rate behavior of Inconel 718 annealed at 1750°F and aged	40
Stress-rupture time behavior of smooth specimens of Inconel 718 annealed at 1750°F and aged	41
Stress-rupture time curves from edge-notched specimens (notch acuities of 2.3 and 6.0) of Inconel 718 annealed at 1750°F and aged	42
Stress versus rupture time behavior of sharp edge-notched specimens of Inconel 718 annealed at 1750°F and aged	43
Stress versus minimum creep rate behavior of Inconel 718 annealed at 1950°F and aged	44
Stress-rupture time curves from smooth specimens of Inconel 718 annealed at 1950°F and aged	45

LIST OF FIGURES (Continued)

FIGURE		PAGE
12	Stress versus rupture time curves from edge-notched specimens ($K_t = 6.0$) of Inconel 718 annealed at 1950°F and aged . . .	46
13	Stress-rupture time behavior of sharp edge-notched specimens of Inconel 718 which were annealed at 1950°F and aged . . .	47

INTRODUCTION

Extensive research has been carried out by many laboratories on the applicability of alloys in sheet form in the supersonic transport (SST). Study of the potential usefulness of superalloys has been conducted at the University of Michigan under a grant from the National Aeronautics and Space Administration. The initial direction of the University's program was a survey of the influence of stressed exposure at elevated temperatures on the tensile properties of a number of superalloys. The results of this research, augmented by findings obtained at other laboratories, showed that three superalloys offered promise for possible application in the Mach 3 transport (Ref. 1).

Superalloy sheet materials have been considered for the hottest sections of the skin of the airplane. Certain areas near the engine cells will be likely to encounter temperatures considerably in excess of those to be generated at the leading edges (550° - 650° F).

The criteria employed in the evaluation of the usefulness of the superalloys in SST applications were considerably different from those employed in preliminary survey of the influence of exposure on tensile properties. Because creep and/or rupture can occur at the expected temperatures and because notch sensitivity has been encountered in superalloys at these temperatures the following material characteristics have been studied:

1. Stress for rupture in 50,000 hours as obtained by extrapolation of stress-rupture time curves based on tests out to about 5,000 hours.
2. Stress-minimum creep rate behavior with emphasis on the stress to produce 0.1 percent creep in 50,000 hours.
3. Stress-rupture time behavior of ASTM sharp edge-notched specimens under a stress of 40,000 psi.

These material properties and characteristics were investigated for several reasons. The SST will be designed to have an operating life of 30,000 to 50,000 hours. It certainly will be necessary to avoid rupture during the service life and, in addition, maintenance of geometrical requirements indicates that creep will have to be limited to small amounts. Normally creep strength would be expected to control load carrying ability, however, comparison of this to rupture strength is necessary since these properties are not always in agreement. Sharp edge-notched specimen properties were studied because of the need of a measure of the sensitivity of cracks or notches to creep conditions.

Two of the three promising superalloys, René 41 and Waspaloy, have already been subjected to an intensive study in which their upper use temperatures were determined. The results of this detailed study (Ref. 2) showed both alloys to have maximum application temperatures of approximately 800°F. These two alloys were found to be subject to failure at unexpectedly low loads during static (creep-rupture) exposure of ASTM sharp edge-notch specimens at 1000° and 1200°F. The research indicated that even dull notches could be expected to induce rupture at low stresses or in short time periods under the nominal design stress of 40,000 psi.

The current report presents the results of an investigation designed to measure the applicability of the third promising alloy to the supersonic transport. This alloy was Inconel 718. This material was of particular interest because of its reported excellent fabricability and weldability.

Some data were obtained during this investigation to extend the findings of the preliminary survey. Prolonged exposures under stress at 800°F were used to measure the stability of the alloy as revealed by room temperature tensile tests.

EXPERIMENTAL MATERIAL

Inconel 718 differs appreciably from most other nickel-base superalloys. This alloy is strengthened through the precipitation of a nickel-titanium-columbium compound as compared to the nickel-aluminum-titanium compound found in most other alloys of this type. Since the precipitation reaction in Inconel 718 is comparatively sluggish the alloy is relatively easy to fabricate. In addition, Inconel 718 has excellent weldability, a characteristic not always found in superalloys.

The Inconel 718 alloy used in this investigation was received in the form of 0.025-inch thick sheet material. One sheet, 24 inches wide by 72 inches long, was received from the producer in each of the following conditions:

- (1) As cold worked - 24 percent cold reduction.
- (2) Cold worked plus annealed for 1 hour at 1750°F.
- (3) Cold worked plus annealed for 1 hour at 1950°F.

Specimen blanks were sheared from each of the sheets. These blanks were then aged prior to being machined into finished specimens. The

aging treatments employed for the alloy in each of its conditions were as follows:

<u>Condition</u>	<u>Aging Treatment</u>
As cold reduced	1325°F/8 hours, F. C. to 1150°F in 10 hours, A. C.
1750°F anneal	1325°F/8 hours, F. C. to 1150°F in 10 hours, A. C.
1950°F anneal	1350°F/8 hours, F. C. to 1200°F in 12 hours, A. C.

F. C. - Furnace cooled
A. C. - Air cooled

The reported chemical composition of the experimental material in weight percent was:

<u>C</u>	<u>Mn</u>	<u>Fe</u>	<u>Ni</u>	<u>Cr</u>	<u>Al</u>	<u>Ti</u>	<u>Co</u>
3.04	0.18	19.16	52.0	18.68	0.33	1.01	0.0
<u>Mo</u>	<u>Cb+Ta</u>	<u>B</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Cu</u>	
3.07	5.19	0.0025	0.009	0.007	0.27	0.04	

EXPERIMENTAL PROCEDURES

The potential usefulness of the alloy in each of the three conditions of prior treatment was studied by tests at 800°, 1000° and 1200°F. The test program consisted of tensile, creep and stress-rupture tests on smooth and edge-notched specimens. The properties were measured in both the longitudinal and transverse orientations in order to avoid misleading results which might be caused by material anisotropy.

Test Specimens

Two types of specimens were employed in this investigation, notched and unnotched. Most of the notched specimens contained the ASTM sharp edge-notch. In addition, some tests were conducted on specimens containing less severe notches.

Unnotched specimens. - The configuration of the smooth specimens used to measure unnotched specimen properties is shown in Figure 1a. These specimens were prepared from rectangular bundles of specimen blanks by a milling operation. Approximately ten specimens were machined at one time, using a fixture to clamp the blanks together and thereby

assure accurate alignment throughout the milling operation.

Notched specimens. - In addition to the ASTM sharp edge-notched specimens, rupture tests were conducted on longitudinal specimens containing milder notches. Specimens containing notches with K_t 's (theoretical elastic stress concentration factor) of 2.3 and 6.0 were prepared. The geometry of these specimens is shown in Figure 1b. In these specimens only the notch root radius was changed to vary the notch acuity. The values of the notch root radius for the different notch acuities were as follows:

<u>Elastic Stress Concentration Factor, K_t</u>	<u>Notch Root Radius, inch</u>
2.3	0.10
6.0	0.010
>20 (ASTM sharp edge-notch)	<0.0007

Most of the research utilized the ASTM sharp edge-notch specimen. This notch simulated an actual crack in the specimen. The configuration of this specimen is shown in Figure 1c. As was the case with the unnotched specimens, ten blanks were machined at one time, using a second fixture to maintain alignment. The reduced section of the specimen was first milled to size. The notches were then ground almost to size using an alundum wheel having a 60-degree included angle. The notch root radii of the specimens of low and intermediate acuity were lapped to final dimensions. The final radii of the sharp notches were obtained by drawing a sharp carbide tool through the notches. Root radii and net section widths were then measured using a 50X optical comparator.

Creep and Rupture Tests

The creep and stress-rupture tests were conducted in individual University of Michigan creep-testing machines. In these units, the stress is applied through a third-class lever system having a lever arm ratio of about 10 to 1. The specimen was gripped by means of pins passed through each end of the specimen and into holders which fitted into a universal joint-type assembly for uniaxial loading. Heating was provided by a resistance furnace which fitted over the specimen and holder assembly.

Strain measurements were taken on the smooth specimens by means of a modified Martens optical extensometer system. Extensometer bars in pairs were attached to collars clamped onto the gage section of the specimens. Placed between the pairs of extensometer bars were the stems of mirror assemblies which reflected an illuminated scale located

about five feet in front of the creep unit. The differential movements of the top and bottom pairs of extensometer bars caused a rotation of the mirrors, which was observed through a telescope mounted next to the illuminated scale. As the specimen elongated, a very small movement of the extensometer rods was magnified by the resulting optical lever and converted into a large change in the reflected scale reading. This system permitted the detection of a specimen strain of about 10 millionths of an inch.

Strain measurements were made as each weight was applied during loading. Creep strain was read periodically through the test. When failure occurred an automatic timer was activated by the fall of the specimen holder measuring the rupture time to one-tenth of an hour.

Three thermocouples were attached to each of the creep and rupture specimens at the center and at either end. All the thermocouples were shielded from direct radiation. Prior to starting a test the furnace was heated to within 50°F of the desired temperature. The specimen was then placed in the hot furnace and brought up to the test temperature and distribution in a period of not more than four hours. ASTM recommended practices were followed in controlling the test temperature and distribution.

Strain measurements were not taken on the notched specimens. The procedures followed for the attainment of the proper test temperature and distribution were the same as those used for the unnotched specimens.

In a number of cases the stressed exposure tests were interrupted before rupture of the specimens. In these cases the furnace was turned off at the required time and the specimen was cooled under load to minimize the effects of creep recovery.

Tensile Tests

All tensile tests were conducted with a 60,000-pound capacity hydraulic tensile machine. Unnotched samples were strained at an approximate strain rate of 0.01-inch per inch per minute up to about 2 percent deformation. The strain rate was then increased to about 0.05-inch per inch per minute until failure. Notched specimens were loaded at a rate of 1000 psi net section stress per second.

Strain measurements were made on the unnotched specimens using the extensometer system described previously.

RESULTS

Tensile and creep-rupture tests were conducted on Inconel 718 sheet material for the purpose of determining its potential usefulness in the trisomic transport. This superalloy was tested in three different conditions of thermal history. The results obtained from the alloy in each of its conditions of heat treatment will be presented in separate sections.

Cold Worked and Aged

Tensile properties. - Smooth and ASTM sharp edge-notch specimens of Inconel 718 in the cold worked and aged condition were tensile tested at room temperature, 800°, 1000° and 1200°F. The results of these tests are presented in Table I.

At room temperature and at 800°F the notched specimen strength of the alloy approached the smooth specimen ultimate strength. Above 800°F, however, the notched specimen tensile strength declined more rapidly with increasing temperature than did the smooth specimen ultimate strength. The ratio of the notched specimen strength to the smooth specimen strength was almost 1.0 at 800°F, while at 1000°F it fell to approximately 0.9 and at 1200°F to only 0.8.

The data showed that the smooth specimen properties were independent of orientation. The notched specimen tensile strengths, however, did tend to show some directionality with the transverse results being lower by a small margin.

Creep resistance. - All smooth specimen rupture tests were instrumented to yield creep data. The minimum creep rates measured during these tests are shown in Table II. Figure 2 is a graph of the log of the minimum creep rate as a function of the log of the applied stress. The graph shows that the curves through the 800° and 1000°F data were approximately parallel and had rather low slope. The curve at 1200°F, however, was much steeper and intersected the assumed SST design stress of 40,000 psi at a creep rate sufficiently high to cause 0.1 percent creep to be accumulated in this application in less than 1000 hours.

There did not appear to be any significant influence of specimen orientation on the observed minimum creep rate. The scatter apparent in the data from transverse specimens at 1200°F is not considered significant.

Rupture properties. - Smooth and notched specimens were subjected to stress-rupture tests at 800°, 1000° and 1200°F. With the exception of the tests conducted at 800°F, the duration of the tests was sufficient to

define the position of the stress-rupture time curve out to several thousand hours. Very few of the tests conducted at 800°F ruptured in reasonable time periods under stresses as high as 98 percent of the reported ultimate tensile strength of the alloy at that temperature.

Smooth specimen results. - The rupture data obtained from the alloy in the cold worked and aged condition are presented in Table II. The stress-rupture time curves plotted from these data are shown in Figure 3. The results at each temperature were independent of specimen orientation with the longitudinal and transverse specimen data falling on the same smooth curve at each temperature.

At 1000°F the stress-rupture time curve was relatively flat, as can be seen in Figure 3. At 1200°F, however, the rupture curve was much steeper. The alloy in this condition at the assumed SST design stress of 40,000 psi would rupture in approximately 2,090 hours at 1200°F. This rupture time is much less than the proposed operating life of the supersonic transport.

Results from notched specimens. - Notches with theoretical elastic stress concentration factors (K_t) of 2.3, 6.0 and >20 (ASTM sharp edge-notch specimen) were used in the investigation. All of the notched specimen rupture test results are listed in Tables III and IV.

The results obtained from the specimens containing the mild notch ($K_t = 2.3$) were difficult to interpret. At both 1000° and 1200°F these specimens tended to fracture at the pin hole rather than in the reduced section. Since over half of these specimens fractured at this location no attempt has been made to qualitatively evaluate the influence of the mild notch on rupture properties. The specimens which did not fail at the pin hole, however, had rupture times close to those exhibited by smooth specimens.

The specimens containing the notch of intermediate acuity ($K_t = 6.0$) had rupture times which paralleled the smooth specimen rupture times but at a lower level. The level was not as low, however, as was shown by the sharp edge-notch specimens. These results are shown in Table III and are plotted in Figure 4. A small amount of scatter in the 1000°F results was evident. This scatter was not present at 1200°F. The total number of these tests was too small and the duration of the tests too brief to allow extrapolation of the results to long times with a high degree of confidence.

The results obtained from the specimens containing the ASTM sharp edge-notch are plotted in Figure 5. These results are also presented in Table IV. The rupture times shown by these specimens were remarkable for their lack of variability. The results did show that some anisotropy was present in the sheet. Among the data obtained from the alloy in

either the longitudinal or the transverse direction, however, very little scatter was evident. This can be seen in Figure 5.

At both 1000° and 1200°F the longitudinal specimens showed higher rupture strength than did the transverse specimens. The absolute level of the transverse specimen properties was very low at 1000°F. Under the expected SST design stress of 40,000 psi at this temperature a transverse specimen ruptured in just over 500 hours. At 1200°F, under the same stress, the rupture time was less than 10 hours. Data obtained from specimens taken in the longitudinal sheet direction indicate rupture times of approximately 10,000 hours and 40 hours at 1000° and 1200°F, respectively, under 40,000 psi stress.

The results obtained at 1200°F, while they lay at a relatively low level, suggest that an upward break exists in the stress-rupture time curve. A similar upward break or leveling off should occur in much longer times at 1000°F. This type of behavior has been noted previously in other nickel-base superalloys (Ref. 2).

Discontinued tests. - A number of tests were interrupted prior to rupture. With one exception all of these tests had been conducted at 800°F. Four unnotched specimens had been exposed at 800°F under stresses from 180,000 psi to 188,000 psi for times between 1000 and 1300 hours. During this time period these specimens had crept only an insignificant amount and for this reason the tests were discontinued. Tensile tests were run on these specimens at room temperature with the results which are shown in Table V. The stressed exposure only had a very minor influence on subsequent ultimate tensile strength. The exposure did cause the 0.2 percent offset yield strength to be raised in three out of the four specimens.

The tensile properties of two ASTM sharp edge-notched specimens were reduced as the result of the stressed exposure (Table VI). These specimens had been exposed for 1000 hours at 800°F and under stresses of 160,000 and 170,000 psi. Examination of the fractured surface of these specimens after room temperature tensile testing indicated that small cracks had propagated a short way into the specimen from the root of the notch during the 800°F exposure. These small cracks reduced the cross-sectional area of the specimen and thereby presumably affected the measured tensile strength.

One specimen containing the sharp edge-notch was interrupted after 5500 hours at 1200°F under a stress of 25,000 psi. This was done because the stress-rupture time curve exhibited an upward break which indicated a rupture life well in excess of 5500 hours. Examination of this specimen, however, showed that a crack had formed at the root of the notch and had propagated about 15 percent of the way across the

specimen. The presence of this large crack was taken as evidence of imminent failure had the test not been discontinued. This specimen was not tensile tested.

Annealed at 1750°F and Aged

Tensile properties. - Similar tests were conducted on the 1750°F annealed and aged material as were run on the alloy in the cold worked and aged condition. Table VII lists the ultimate tensile strength, the 0.2 percent offset yield strength, the elongation and the notched specimen tensile strength at room temperature, 800°, 1000° and 1200°F. The data in this table are grouped to show the influence of specimen orientation on properties.

The trend of the results was as expected with the exception of the rather low longitudinal notch specimen strengths at 800° and 1000°F. A more gradual fall off in strength would have been expected with increasing temperature.

Creep strength. - The minimum creep rate data obtained from the smooth specimen rupture tests are recorded in Table VIII. These data are plotted as a function of stress in Figure 6. The straight lines drawn through the 800° and 1000°F data were parallel to each other and had rather low slopes as can be seen in Figure 6. The 1200°F curve had a much greater slope than did the curves drawn through the lower temperature data. The extrapolation of this curve intersects the expected SST design stress of 40,000 psi at a minimum creep rate of 0.00003 percent per hour. This can be interpreted as implying that in approximately 3000 hours at 1200°F under 40,000 psi, Inconel 718 in the 1750°F annealed and aged condition will accumulate 0.1 percent creep deformation.

No significant difference in minimum creep rate with respect to specimen orientation was noted at any of the temperatures investigated. In every case the minimum creep rates fell on a smooth curve when plotted as a function of stress.

Rupture strength. - Rupture tests were conducted on smooth and edge-notched specimens at 800°, 1000° and 1200°F. The tests carried out at 800°F did not fail in reasonable time periods even though the stresses involved were very large fractions of the tensile strength. These tests were therefore discontinued and tensile tests were conducted on the interrupted specimens. These results will be presented in a following section.

Smooth specimen results. - The rupture data obtained from the tests at 1000° and 1200°F are listed in Table VIII. At 1000°F the tests con-

tinued for times as long as 5000 hours while at 1200°F the maximum length of time was approximately 1250 hours. The stress-rupture time curves at these two temperatures are shown in Figure 7.

The stress-rupture time curve at 1000°F was fairly flat. At the shorter times there was no apparent influence of specimen orientation on rupture time. At the longer times, however, the longitudinal specimens failed in shorter times than did the specimens with a transverse orientation. The difference may not be significant and may well only be an indication of specimen variability. The same apparent effect was not noted at 1200°F. The 1200°F data lay on a smooth curve which had a somewhat steeper slope than the 1000°F rupture curve. The extrapolated 50,000 hour rupture strength at 1200°F was 40,000 psi which corresponded to the expected design stress for superalloys in the SST.

The rupture ductility of the specimens decreased with increasing time. While the elongation values were higher at 1200°F than at 1000°F, a specimen which fractured after 5006 hours at 1000°F still exhibited almost 3 percent elongation.

Notched specimen rupture properties. - The specimens containing the mild notches ($K_t = 2.3$) were rupture tested at 1000° and 1200°F with the results listed in Table IX and shown in Figure 8. Their properties were very similar to the properties exhibited by the smooth specimens. As an example, Table XI shows the comparative 1000 hour strengths of smooth and notched specimens of Inconel 718 in each of its conditions of prior history. For the alloy in the 1750°F annealed and aged condition the 1000 hour rupture strength of the mildly notched specimens ($K_t = 2.3$) at 1000°F was 135,000 psi as compared with 145,000 psi for the smooth specimens. At 1200°F the values were 65,000 psi and 68,000 psi, respectively. In addition, the rupture curves drawn through the data from the smooth specimens and from the mildly notched specimens were approximately parallel at both 1000° and 1200°F.

The rupture tests conducted on specimens with edge notches of intermediate acuity ($K_t = 6.0$) also yielded 1000 hour strengths in fairly close agreement with the smooth specimen results, as can be seen in Table XI. At 1000°F the 1000 hour rupture strength of these specimens was 125,000 psi as compared to 145,000 psi of the unnotched specimens while at 1200°F the rupture strength was only 3000 psi lower, 65,000 psi compared to 68,000 psi for the smooth specimens.

Tests were carried out at 800°, 1000° and 1200°F on specimens containing the ASTM sharp edge-notch ($K_t > 20$). The results of these tests are listed in Table X. The tests conducted at 800°F gave inconsistent results. As an example, one specimen fractured on loading while a

second specimen loaded to a higher stress failed in 850 hours and a third specimen tested at a still higher stress was discontinued after 3300 hours because of a lack of any indication of impending fracture.

At 1000° and 1200°F the sharp edge-notched specimens of the alloy in the 1750°F annealed and aged condition showed excellent rupture strengths (Table X) as compared to other superalloys (Ref. 2). This was particularly true at longer testing times where the rupture curves for the two temperatures were very close together. This behavior is shown in Figure 9. If these unusual properties are reasonably correct then the use of the alloy in this condition in the supersonic transport should be limited temperature-wise by factors other than notch sensitivity.

The notched specimen properties of Inconel 718 alloy in this condition of prior history are quite high as compared with other nickel-base superalloys which have been studied at the University (Ref. 2). This is particularly true at 1200°F where the notched specimen properties approach those of the smooth specimens. At 1000°F, while the notched specimen properties were very good, especially the properties shown by specimens containing notches of low and intermediate acuities, the sharp edge notched specimens gave rupture strengths which were somewhat less than half those exhibited by unnotched specimens. This can be seen in Table XI.

Interrupted tests. - Three longitudinal and three transverse smooth specimens were discontinued after exposure to stresses in the range from 160,000 psi to 170,000 psi at 800°F for times varying between 1000 and 5180 hours. The creep data taken during these tests indicated very long rupture times. Room temperature tensile tests were subsequently run on these specimens with the results which are given in Table V. The comparison of these data to the results from unexposed specimens showed that the ultimate strength was raised slightly as a consequence of the prolonged stressed exposure. The 0.2 percent offset yield strength, however, was raised appreciably; from approximately 173,000 psi for the unexposed specimen to 191,000 psi for a specimen exposed for 1000 hours to 211,600 psi for a specimen interrupted after 5180 hours. The stressed exposure also probably caused the tensile elongation to be very slightly reduced.

Three notched specimens were found to be slightly cracked as the result of the stressed exposure at 800°F. Although the specimens were dye checked the cracks were not discovered in two of the specimens until the room temperature tensile tests were completed. The tensile results as well as the conditions of the exposure are shown in Table VI. The reduction in notch specimen strength was probably due to the small cracks found at the root of the notch.

Annealed at 1950°F and Aged

Tensile properties. - The tensile properties recorded from different specimens tested at room temperature, 800°, 1000° and 1200°F are listed in Table XII. Both smooth and sharp edge-notched specimens were used. Over the range of temperature studied the notched specimen strength properties approached those of the smooth specimens. The notch strength-tensile strength ratio was essentially constant at a level of about 0.96 at the different test temperatures.

On the average the longitudinal specimens had slightly higher properties than did the transverse specimens. It is doubtful that this slight difference in strength level was significant.

Creep resistance. - The minimum creep rates measured during the rupture tests are recorded in Table XIII. A log-log graph of minimum creep rate as a function of stress is shown in Figure 10. This graph shows the creep resistance of the alloy in this condition to be quite high, particularly at 1200°F. In both of the other conditions of prior history evaluated in this investigation, the creep resistance of the Inconel 718 specimens fell off badly at 1200°F. This is shown in Figures 2 and 6 as a steep slope to the stress versus minimum creep rate curve at 1200°F as compared to the 800° and 1000°F curves. Figure 10 shows the curves of minimum creep rate versus stress to be almost parallel at all temperatures with the 1200°F curve being only slightly greater in slope than the curves through the 800° and 1000°F data. No evidence of any difference in creep resistance with specimen orientation was indicated by the data.

Rupture properties. - Rupture tests were run at 800°, 1000° and 1200°F. Specimens which survived initial loading at 800°F did not rupture in times out to 4340 hours under stresses which approached the tensile strength of the alloy. As a consequence the smooth specimen tests at this temperature were discontinued.

Smooth specimen rupture properties. - The results of rupture tests at 1000° and 1200°F on unnotched specimens are plotted as a function of stress in Figure 11. The curves through these data are relatively flat at both 1000° and 1200°F as can easily be seen in this graph. While the data do show some variability it is not considered to be significant enough to prevent the drawing of one smooth curve through these data at each temperature. No evidence of anisotropy is present.

The 1200°F stress-rupture time curve is relatively flat. Extrapolation of the curve indicates that the 50,000 hour rupture strength will be approximately 55,000 psi at 1200°F while at 1000°F it should be about twice that level.

Notched specimen properties. - The notched specimen rupture properties of the alloy in the 1950°F annealed and aged condition were relatively poor, especially when they were compared to the properties in the 1750°F annealed and aged condition.

The mild notched specimens ($K_t = 2.3$) showed very erratic rupture results. These data are shown in Table XIV. At 1000°F the rupture times showed no relation to the applied stress. At 1200°F two of the specimens ruptured through the pin hole used to transmit the load to the specimen. The lack of any trend to these data made it impossible to arrive at a quantitative expression of the influence of the mild edge-notch on the properties of the alloy in this condition.

The specimens containing the notch of intermediate acuity ($K_t = 6.0$) had the properties shown in Table XIV. The data obtained from these specimens, in marked contrast to the milder notched specimens, showed almost no scatter. These data are shown in Figure 12. The stress-rupture time curve through the 1000°F data showed a more pronounced slope than did the curve through the 1200°F data. Since steeper slopes are usually associated with higher temperatures it is probable that the reverse indicates that an upward break in the 1000°F rupture curve will be found at sometime beyond 1000 hours.

The sharp edge-notched specimen rupture data are shown in Table XV. In contrast to the results from the alloy in the other two conditions of prior history, a sufficient number of specimens fractured at 800°F to allow for the positioning of a rupture curve at that temperature. These data are different from the data for Inconel 718 with the other treatments in that some anisotropy is shown. At 1000° and 1200°F the specimens taken in the transverse direction had superior rupture strength to specimens with the longitudinal orientation. The stress-rupture time curves are shown in Figure 13. The absolute position of these curves are low relative to other superalloys, particularly at 1200°F.

The comparison of the influence of prior history and specimen geometry on 1000 hour rupture strength (Table XI) shows that the notched specimen properties of the alloy in the 1950°F annealed and aged condition were poor at 1200°F while the smooth specimen properties were good. At 1000°F the notched specimen properties were better than those shown by the alloy in the cold worked and aged condition and approached the properties of the alloy in the 1750°F annealed and aged condition.

Interrupted tests. - Four smooth specimens were discontinued after exposure for times up to 4340 hours at 800°F under stresses ranging from 155,000 psi to 165,000 psi. Room temperature tensile tests were run on these specimens with the results shown in Table V. Comparison of these results with the properties exhibited by the unexposed specimens

showed that the ultimate tensile strength had not changed although the 0.2 percent offset yield strength had increased somewhat as the result of the stressed exposure. The tensile elongations were approximately the same before and after the 800°F stressed exposure.

DISCUSSION

The primary objective of this investigation was the evaluation of the potential usefulness of Inconel 718 sheet material in the supersonic transport. It was assumed that any application of the alloy would be limited to the hottest sections of the craft and as a consequence it was decided to judge the alloy's potential usefulness on its creep and rupture properties.

Creep-rupture data from Inconel 718 sheet alloy in three different conditions of heat treatment have been presented. These data showed the properties of the alloy to vary significantly with thermal history.

Influence of Heat Treatment on Strength

Rupture strength. - One comparison of the rupture strength of Inconel 718 sheet material as a function of prior thermal treatment was made in Table XI. This table showed the 1000 hour rupture strength of smooth and edge-notched specimens at 800°, 1000° and 1200°F. The 1000 hour smooth specimen strength did not vary appreciably with thermal history at 1000°F, however, at 1200°F a wide range of strengths existed. The cold reduced and aged material had a 1000 hour rupture strength of only 44,000 psi at 1200°F compared to 68,000 psi for the alloy annealed at 1750°F and 75,000 psi for the material annealed at 1950°F.

Extrapolation of the smooth specimen stress-rupture time curves showed that a similar variation existed in the stress for rupture in 50,000 hours at 1200°F as was noted at 1000 hours. The extrapolated strengths are given in the following tabulation:

<u>Condition</u>	<u>Stress for rupture in 50,000 hours at:</u>	
	<u>1000°F</u>	<u>1200°F</u>
Cold worked and aged	98,000 psi	22,000 psi
Annealed at 1750°F and aged	115,000 psi	40,000 psi
Annealed at 1950°F and aged	110,000 psi	55,000 psi

The time of 50,000 hours was selected for the comparison of rupture strength with thermal treatment because it corresponded to the expected design life of the supersonic transport. These values when compared to

the estimated design stress of 40,000 psi indicate that the potential usefulness of Inconel 718 sheet material in the SST could be limited to applications at 1200°F or less by rupture strength. The alloy in the cold worked and aged condition certainly does not have sufficient rupture strength to be used at 1200°F under the expected design conditions. In the 1750°F annealed and aged condition the alloy has only marginal strength for use at 1200°F. The alloy when annealed at 1950°F, however, had an extrapolated 50,000 hour rupture strength of 55,000 psi which is well above the expected design stress.

Creep resistance. - Design criteria will limit tolerable deformation in the skin of the SST to approximately 0.1 percent over its service life. Translating this amount of total deformation into a minimum creep rate involves making assumptions of questionable reliability. For this reason the stress to cause a given minimum creep rate can only approximate the stress which will cause a certain amount of creep deformation to be accumulated in a given time period. In order to compare the properties of the alloy in its different conditions it has been assumed that the stress required to produce a minimum creep rate of 0.000001 percent per hour will approximate the stress to cause the accumulation of 0.1 percent deformation in 50,000 hours.

The creep resistance of Inconel 718 sheet material has been shown to vary significantly at 1200°F with prior thermal history. Such a wide variation in creep resistance was not evident at either 800° or 1000°F, as can be seen in the following tabulation:

<u>Condition</u>	<u>Extrapolated Stress necessary to produce a minimum creep rate of 0.000001%/hr:</u>		
	<u>800°F</u>	<u>1000°F</u>	<u>1200°F</u>
Cold worked and aged	175,000 psi	112,000 psi	10,000 psi
Annealed at 1750°F and aged	150,000 psi	110,000 psi	26,000 psi
Annealed at 1950°F and aged	155,000 psi	114,000 psi	59,000 psi

Comparison of these values with those previously listed showing the extrapolated stress for rupture in 50,000 hours emphasizes the degree of uncertainty in the original assumption of the equivalence of the stress required to produce 0.1 percent creep in 50,000 hours and the stress for a minimum creep rate of 0.000001 percent per hour. In several cases the stress to produce a minimum creep rate of 0.000001 percent per hour was greater than the stress for rupture in 50,000 hours. If the basic assumptions are correct then rupture would have to occur at total deformation of less than 0.1 percent. It is unlikely that this would be the case.

The low 1200°F creep strength of the alloy in the cold worked and aged condition and in the 1750°F annealed and aged condition could possibly restrict the upper temperature of application of Inconel 718 in these two conditions of thermal history. Smooth specimens of the alloy annealed at 1950°F and aged, however, have both high creep strength and high rupture strength at temperatures of up to 1200°F.

Notched specimen properties. - Poor notched specimen properties would be expected to limit the potential utility in the SST of two titanium + aluminum hardened nickel-base superalloys, René 41 and Waspaloy (Ref. 2). It has been suggested that the notch sensitivity of these alloys may have been caused by strain induced precipitation of γ' in the plane of the notch. Unpublished research at the University of Michigan has shown that strain induced precipitation of γ' does occur in these materials. Whether this was the cause of the poor notched specimen properties, however, has not as yet been established.

Since Inconel 718 is reportedly strengthened by a somewhat more sluggish precipitation reaction than either René 41 or Waspaloy, it was anticipated that its notched specimen properties might be somewhat better. Estimated rupture times of ASTM sharp edge-notched specimens of Inconel 718 in each of the three conditions of prior thermal history are shown in the following table. The same methods of evaluation of the notched specimen data were employed as were used in the earlier study of René 41 and Waspaloy. These methods involved the estimation of minimum rupture times of sharp edge-notched specimens under a stress of 40,000 psi at 800°, 1000° and 1200°F.

Minimum time for rupture of sharp edge-notched specimens
under 40,000 psi stress

Condition	800°F	1000°F	1200°F
Cold worked and aged	>10,000 hrs.	500 hrs.	1 hr.
Annealed at 1750°F and aged	>10,000 hrs.	>10,000 hrs.	>10,000 hrs.
Annealed at 1950°F and aged	>10,000 hrs.	>10,000 hrs.	8 hrs.

This tabulation shows that the alloy in the 1750°F annealed and aged condition possessed excellent notched specimen properties up to 1200°F. The properties of the Inconel 718 in the cold reduced and aged condition, however, were poor at 1000°F, just as were the properties of cold worked René 41 and cold worked Waspaloy. The material annealed at 1950°F showed notched specimen properties intermediate to those of the alloy in its other two conditions. Inconel 718 alloy in this condition had excellent notched specimen properties at 1000°F but poor properties at 1200°F.

A comparison of the influence on rupture strength of two mild notches ($K_t = 2.3$ and 6.0) was presented in Table XI. This comparison showed

that both of these notches significantly reduced the 1200°F 1000 hour rupture strength of the alloy in the cold reduced and aged condition and in the 1950°F annealed and aged condition. These notches, however, did not have any marked effect on the strength of the alloy when it was annealed at 1750°F. These data should be considered as further evidence of the drastic influence notches (and cracks) can have on Inconel 718 sheet material if proper heat treatment has not been employed.

Applicability of Results

A previous investigation carried out at the University of Michigan showed that two nickel-base superalloys, René 41 and Waspaloy, had excellent smooth specimen creep and rupture strengths at 1000° and 1200°F but poor notched specimen strength at these same temperatures (Ref. 2). The present investigation has shown properly heat treated Inconel 718 sheet material to have somewhat lower creep and rupture strengths than either René 41 or Waspaloy, but excellent notched specimen properties at temperatures of up to 1200°F.

Inconel 718 sheet material annealed at 1750°F and aged possessed sufficient insensitivity to ASTM sharp edge-notches under creep conditions to have its predicted upper use temperature in the supersonic transport limited by creep resistance. Since sensitivity to sharp edge notches is a measure of the tendency toward catastrophic crack propagation it has been assumed that the alloy, when properly heat treated, can withstand cracks for prolonged lengths of time under SST design conditions.

Less risks are involved in the interpolation of creep and rupture strengths between temperatures than in the interpolation of notched specimen rupture times between temperatures. For this reason and because of the generally promising creep and rupture properties the alloy in the 1750°F annealed and aged condition has been selected as having the most potential for application in the supersonic transport. Based on the results of this investigation, the alloy in this condition should be suitable for service at temperatures up to approximately 1150°F under the assumed design stress of 40,000 psi. If the design stress were changed, the calculated upper use temperature would also be changed.

CONCLUSIONS

An investigation of the tensile, creep and rupture properties of Inconel 718 sheet material at 800°, 1000° and 1200°F has been completed. The alloy was tested in three conditions of prior thermal treatment: (1) cold worked and aged (2) annealed at 1750°F and aged, and (3) annealed at 1950°F and aged. Based on the results of this investigation and on assumed design considerations, the following conclusions have been reached concerning the applicability of Inconel 718 as skin material in the supersonic transport:

1. The alloy in the cold reduced and aged condition is sensitive to the presence of sharp edge-notches at 1000° and 1200°F and therefore could have only limited usefulness in the SST.
2. The alloy annealed at 1950°F possessed high creep and rupture strengths at temperatures of up to 1200°F but poor notched specimen strength above 1000°F.
3. The alloy annealed at 1750°F exhibited excellent notched specimen properties at temperatures of up to 1200°F, however at 1200°F its creep strength was less than, and its rupture strength equal to, the expected SST design stress.
4. The alloy annealed at 1750°F exhibited sufficiently high notched specimen properties as well as creep and rupture strengths at temperatures of up to 1150°F to permit its use up to 1150°F in the supersonic transport under an expected design stress of 40,000 psi.

The conclusions expressed are only intended to apply to Inconel 718 sheet material in the conditions of heat treatment which were used in this investigation. There may well be other heat treatments which could be applied to the alloy which would result in better elevated temperature properties than those measured in this research. In addition, there may be changes possible in chemical composition within the specified compositional limits which would result in significant improvement in high temperature properties. Finally, any difference in design criteria from those assumed in this investigation will result in a change in the predicted upper use temperature of the alloy.

REFERENCES

1. Raring, R. H., Freeman, J. W., Schultz, J. W., and Voorhees, H. R.: Progress Report of the NASA Special Committee on Materials Research for Supersonic Transports. NASA TN D-1798, May 1963.
2. Cullen, T. M., and Freeman, J. W.: The Mechanical Properties at 800°, 1000° and 1200°F of Two Superalloys Under Consideration for Use in the Supersonic Transport. NASA CR-92, September 1964.

TABLE I

Summary of Tensile Results Obtained from Smooth and Sharp Edge-Notched Specimens of Inconel 718 - Cold Worked 20 Percent and Aged

Specimen Code	Orientation	Temp. °F	Ultimate Strength ksi	0.2% Offset Yield Strength, ksi	Elong. %
<u>Smooth Specimens</u>					
IN1LS4	Long.	R. T.	218.0	207.0	9.5
IN1TS4	Trans.	R. T.	217.0	203.5	7.5
IN1LS1	Long.	800	185.8	174.0	9.5
IN1TS1	Trans.	800	190.0	178.0	9.5
IN1LS2	Long.	1000	183.3	170.0	12.0
IN1TS2	Trans.	1000	184.6	173.0	7.0
IN1LS3	Long.	1200	174.5	115.0	10.0
IN1TS3	Trans.	1200	173.5	158.8	8.5
<u>Edge-Notched Specimens</u>					
IN1LN1	Long.	R. T.	219.5		
IN1TN1	Trans.	R. T.	204.5		
IN1LN2	Long.	800	170.2		
IN1LN7	Long.	800	186.5		
IN1TN2	Trans.	800	181.2		
IN1LN3	Long.	1000	170.5		
IN1TN3	Trans.	1000	160.5		
IN1LN4	Long.	1200	141.0		
IN1TN4	Trans.	1200	134.5		

TABLE II

Summary of Test Results from Smooth Specimens of Inconel 718 -
Cold Worked 20 Percent and Aged Condition

Specimen Code	Orientation	Temp. °F	Stress ksi	Rupture Time, hrs.	Elong. %	Minimum Creep Rate, %/hr.
IN1LS14	Long.	800	184	>1000 ^a		0.0000185
IN1LS5	"	"	180	>1300 ^b		0.000017
IN1TS14	Trans.	800	188	>1100 ^c		0.00004
IN1TS5	"	"	185	>1300 ^b		0.00004
IN1LS6	Long.	1000	175	42.2 ^d	3.0	0.030
IN1LS7	"	"	170	61.6 ^d	2.3	0.0164
IN1LS11	"	"	160	207.0 ^e	1.8	0.00216
IN1LS10	"	"	150	228.4 ^d	3.0	0.00038
IN1LS17	"	"	135	1876.6 ^d	2.0	0.000046
IN1TS6	Trans.	1000	175	34.5 ^d	4.0	0.057
IN1TS7	"	"	170	73.6 ^d	2.0	0.017
IN1TS11	"	"	160	80.4 ^e	1.0	0.0040
IN1TS10	"	"	150	143.7 ^e	1.5	0.00148
IN1TS16	"	"	150	346.0 ^f		
IN1TS15	"	"	135	438.6 ^f		0.00016
IN1TS19	"	"	125	921.6 ^f		0.000033
IN1LS8	Long.	1200	150	0.7 ^d	3.0	
IN1LS9	"	"	100	15.5 ^e	1.5	
IN1LS12	"	"	75	40.2 ^e	1.25	0.0022
IN1LS13	"	"	60	172.8 ^e	1.25	0.00055
IN1LS15	"	"	50	639.1 ^f		0.000225
IN1LS16	"	"	40	2498.9 ^d	1.25	0.000120
IN1TS8	Trans.	1200	150	0.4 ^d	2.5	
IN1TS9	"	"	100	10.3 ^e	1.0	
IN1TS12	"	"	75	48.2 ^e	1.5	0.0019
IN1TS13	"	"	60	103.2 ^e	1.0	0.00020
IN1TS17	"	"	50	530.4 ^d	0.5	0.00033
IN1TS18	"	"	40	1809.3 ^d	1.0	0.000187

a - Interrupted after 1000 hours

b - Interrupted after 1300 hours

c - Interrupted after 1100 hours

d - Fractured beneath collar

e - Fractured at base of fillet

f - Fractured at pin hole

TABLE III

Summary of Test Results from Notched Specimens of Inconel 718 -
Cold Worked 20 Percent and Aged Condition

Specimen Code	Stress Concentration Factor, K_t	Temp. °F	Stress ksi	Rupture Time hours
IN1LN25	2.3	1000	160	47.0
IN1LN24	"	"	150	154.6 ^a
IN1LN26	"	"	140	34.8
IN1LN27	"	"	130	454.4 ^a
IN1LN23	2.3	1200	70	67.4 ^a
IN1LN21	"	"	60	190.2
IN1LN22	"	"	50	363.0 ^a
IN1LN34	6.0	1000	135	94.0
IN1LN32	"	"	120	233.6
IN1LN35	"	"	110	86.2
IN1LN37	"	"	100	331.4
IN1LN39	"	"	90	803.1
IN1LN31	6.0	1200	50	87.7
IN1LN36	"	"	45	255.8
IN1LN33	"	"	40	464.4
IN1LN38	"	"	36	1400.9

a - Fractured at pin hole

TABLE IV

Summary of Test Results from Sharp Edge-Notched Specimens of
Inconel 718 - Cold Worked 20 Percent and Aged Condition

Specimen Code	Orientation	Temp. °F	Stress ksi	Rupture Time hours
IN1LN8	Long.	800	180	0 ^a
IN1LN13	"	"	175	0 ^a
IN1LN14	"	"	170	>1000 ^b
IN1LN41	"	"	165	1717.7
IN1TN7	Trans.	800	175	0 ^a
IN1TN13	"	"	165	0 ^a
IN1TN12	"	"	160	>1004.5 ^b
IN1TN20	"	"	155	1383.0
IN1TN22	"	"	150	>2064
IN1LN6	Long.	1000	150	12.5
IN1LN11	"	"	130	28.4
IN1LN12	"	"	110	73.0
IN1LN17	"	"	90	226.0
IN1LN18	"	"	80	227.8
IN1LN19	"	"	70	633.4
IN1LN20	"	"	60	1787.5
IN1TN6	Trans.	1000	150	2.0
IN1TN10	"	"	130	7.4
IN1TN11	"	"	110	9.9
IN1TN16	"	"	90	25.8
IN1TN17	"	"	70	71.3
IN1TN18	"	"	50	220.8
IN1TN19	"	"	40	513.8
IN1TN21	"	"	35	>2064
IN1LN5	Long.	1200	75	1.3
IN1LN9	"	"	55	10.3
IN1LN10	"	"	40	40.1
IN1LN42	"	"	36	>2064
IN1LN15	"	"	30	3590.7
IN1LN16	"	"	25	>5518.1
IN1TN5	Trans.	1200	75	0.3
IN1TN8	"	"	55	0.6
IN1TN9	"	"	40	6.3
IN1TN14	"	"	30	5.1
IN1TN15	"	"	25	1052.5

a - Fractured on loading

b - Interrupted after 1000 hours

TABLE V

Influence of Stressed Exposure at 800°F on Tensile Strength

Specimen Code	Exposure Conditions		Orientation	Room Temperature Properties		
	Stress Ksi	Time Hours		Ultimate Strength, Ksi	0.2% Offset Yield Strength, Ksi	Elong. %
<u>Cold Worked and Aged</u>						
IN1LS4	0	0	Long.	218.0	207.0	9.5
IN1LS14	184	1000	"	224.0	222.0	7.0
IN1LS5	180	1300	"	218.8	205.0	8.5
IN1TS4	0	0	Trans.	217.0	203.5	7.5
IN1TS14	188	1100	"	225.4	225.0	8.5
IN1TS5	185	1300	"	220.8	219.9	4.5
<u>Annealed at 1750°F and Aged</u>						
IN2LS1	0	0	Long.	207.5	173.5	17.3
IN2LS15	170	4463	"	209.6	204.0	15.3
IN2LS16	165	1000	"	207.8	195.5	17.3
IN2LS17	160	1000	"	208.9	191.0	18.0
IN2TS1	0	0	Trans.	206.0	173.0	18.0
IN2TS9	175	5180	"	211.7	211.6	14.8
IN2TS15	170	3280	"	207.6	197.0	17.5
IN2TS14	165	1000	"	208.5	202.0	16.3
<u>Annealed at 1950°F and Aged</u>						
IN3LS1	0	0	Long.	204.0	176.5	20.5
IN3LS11	165	4340	"	200.0	194.0	15.8
IN3LS15	160	1000	"	198.4	189.0	20.8
IN3TS16	0	0	Trans.	198.5	168.0	21.0
IN3TS11	160	4340	"	196.0	189.0	18.5
IN3TS15	155	1000	"	194.0	183.0	20.0

TABLE VI

Influence of Stressed Exposure on Notch Strength

Specimen Code	Exposure Conditions			Specimen Orientation	Room Temperature
	Temp. °F	Stress Ksi	Time Hours		Notch Strength Ksi.
<u>Cold Worked and Aged</u>					
IN1LN1		Not Exposed		Longitudinal	219.5
IN1LN14	800	170	1000	"	196.0 ^a
IN1LN16	1200	25	5578	"	(b)
IN1TN1		Not Exposed		Transverse	204.5
IN1TN12	800	160	1000	"	190.0 ^a
<u>Annealed at 1750°F and Aged</u>					
IN2LN1		Not Exposed		Longitudinal	187.0
IN2LN14	800	135	3334	"	161.0 ^a
IN2LN11	800	130	4222	"	(b)
IN2TN1		Not Exposed		Transverse	180.0
IN2TN14	800	155	3334	"	177.0 ^a

a - Specimen found to be slightly cracked as the result of exposure

b - Specimen found to be cracked and therefore the tensile test was not conducted.

TABLE VII

Summary of Tensile Results obtained from Smooth and Sharp Edge-Notched Specimens of Inconel 718 - Annealed at 1750°F and Aged

Specimen Code	Orientation	Temp. °F	Ultimate Strength ksi	0.2% Offset Yield Strength, ksi	Elong. %
<u>Smooth Specimens</u>					
IN2LS1	Long.	R. T.	207.5	173.5	17.3
IN2TS1	Trans.	R. T.	206.0	173.0	18.0
IN2LS2	Long.	800	182.5	155.7	20.3
IN2TS2	Trans.	800	179.7	157.5	21.0
IN2LS3	Long.	1000	177.2	153.0	21.5
IN2TS3	Trans.	1000	176.4	151.5	21.0
IN2LS4	Long.	1200	159.4	141.9	11.0
IN2TS4	Trans.	1200	160.0	141.7	10.0
<u>Edge-Notched Specimens</u>					
IN2LN1	Long.	R. T.	187.0		
IN2TN1	Trans.	R. T.	180.0		
IN2LN2	Long.	800	136.0		
IN2TN2	Trans.	800	161.5		
IN2LN3	Long.	1000	132.0		
IN2TN3	Trans.	1000	142.5		
IN2LN4	Long.	1200	138.0		
IN2TN4	Trans.	1200	139.2		

TABLE VIII

Summary of Test Results from Smooth Specimens of Inconel 718 -
Annealed at 1750°F and Aged

Specimen Code	Orientation	Temp. °F	Stress ksi	Rupture Time hours	Elong. %	Minimum Creep Rate, %/hr.
IN2LS9	Long.	800	175	0 ^a		0.000068
IN2LS15	"	"	170	>4462 ^c		
IN2LS16	"	"	165	>1006 ^c		
IN2LS17	"	"	160	>1006 ^c		
IN2TS9	Trans.	800	175	>5182 ^c		0.00005
IN2TS15	"	"	170	>3284 ^c		
IN2TS14	"	"	165	>1006 ^c		
IN2LS14	Long.	1000	165	50.2	10.5	0.092
IN2LS10	"	"	160	92.7	6.0	0.0194
IN2LS7	"	"	150	732.9	4.0	0.0021
IN2LS12	"	"	140	1371.8 ^b	4.0	0.000905
IN2LS8	"	"	130	3754.0	3.5	0.0003
IN2TS13	Trans.	1000	160	112.8	4.8	0.0202
IN2TS7	"	"	150	365.8 ^b	3.0	0.0045
IN2TS12	"	"	140	2226.2	4.3	0.000547
IN2TS8	"	"	130	5006.2	2.8	0.00118
IN2LS5	Long.	1200	100	33.0	8.0	
IN2LS11	"	"	90	131.9	13.0	0.020
IN2LS6	"	"	75	544.1	9.0	0.00315
IN2LS13	"	"	70	972.9	6.8	0.00165
IN2TS5	Trans.	1200	100	67.5	13.8	0.027
IN2TS10	"	"	90	115.1	9.3	0.0122
IN2TS6	"	"	75	479.1	8.3	0.00315
IN2TS11	"	"	65	1254.2	7.3	0.001204

a - Fractured on loading

b - Fractured beneath collar

c - Test Discontinued

TABLE IX

Summary of Test Results from Notched Specimens of Inconel 718 -
Annealed at 1750°F and Aged

Specimen Code	Stress Concentration Factor, K_t	Temp. °F	Stress ksi	Pupture Time hours
IN2LN24	2.3	1000	160	15.0
IN2LN25	"	"	150	85.9
IN2LN26	"	"	140	574.6
IN2LN28	"	"	135	1394.7
IN2LN23	2.3	1200	90	179.7
IN2LN21	"	"	80	478.0
IN2LN22	"	"	70	300.8
IN2LN27	"	"	65	1311.8
IN2LN38	6.0	1000	160	41.6
IN2LN37	"	"	150	128.4
IN2LN36	"	"	140	360.4
IN2LN34	"	"	130	4077.6
IN2LN32	"	"	120	1366.8
IN2LN35	6.0	1200	90	102.7
IN2LN33	"	"	80	173.8
IN2LN31	"	"	70	631.0
IN2LN39	"	"	65	1316.7

TABLE X

Summary of Test Results from Sharp Edge-Notched Specimens of
Inconel 718 - Annealed at 1750°F and Aged

Specimen Code	Orientation	Temp. °F	Stress ksi	Rupture Time hours
IN2LN17	Long.	800	140	1788.2
IN2LN14	"	"	135	>3333.8
IN2LN11	"	"	130	>4222.5
IN2TN14	Trans.	800	155	>3333.9
IN2TN11	"	"	150	848.6
IN2TN16	"	"	145	0 ^a
IN2LN5	Long.	1000	120	6.4
IN2LN6	"	"	100	6.9
IN2LN12	"	"	90	55.7
IN2LN9	"	"	80	267.8
IN2LN13	"	"	74	321.5
IN2LN15	"	"	70	395.4
IN2LN16	"	"	65	1771.3
IN2TN5	Trans.	1000	120	0 ^a
IN2TN6	"	"	100	20.0
IN2TN9	"	"	70	371.0
IN2TN12	"	"	74	288.6
IN2TN15	"	"	70	793.7
IN2TN17	"	"	66	1540.9
IN2LN8	Long.	1200	80	11.2
IN2LN10	"	"	70	21.2
IN2LN7	"	"	60	1032.8
IN2TN3	Trans.	1200	80	7.2
IN2TN10	"	"	70	276.1
IN2TN7	"	"	60	682.2
IN2TN13	"	"	55	1206.6

a - Fractured on loading

TABLE XI

Comparison of 1000 Hour Rupture Strengths

Stress Concentration Factor, K_t	Temperature		
	800°F	1000°F	1200°F
<u>Cold Worked and Aged</u>			
1.0 (Smooth)	185,000 psi	125,000 psi	44,000 psi
2.3	-	-	-
6.0	-	88,000 psi	37,000 psi
>20	160,000 psi	35,000 psi ^a	25,000 psi
<u>Cold Worked, Annealed at 1750°F and Aged</u>			
1.0 (Smooth)	170,000 psi	145,000 psi	68,000 psi
2.3	-	135,000 psi	65,000 psi
6.0	-	125,000 psi	65,000 psi
>20	140,000 psi	65,000 psi	55,000 psi
<u>Cold Worked, Annealed at 1950°F and Aged</u>			
1.0 (Smooth)	160,000 psi	135,000 psi	75,000 psi
2.3	-	-	49,000 psi
6.0	-	87,000 psi	37,000 psi
>20	155,000 psi	60,000 psi ^b	31,000 psi ^c

a - Transverse direction, in longitudinal direction 1000 hour strength
= 65,000 psi

b - Longitudinal direction, in transverse direction 1000 hour strength
= 77,000 psi

c - Longitudinal direction, in transverse direction 1000 hour strength
= 41,000 psi

TABLE XII

Summary of Tensile Results obtained from Smooth and Sharp Edge-
Notched Specimens of Inconel 718 - Annealed at 1950°F and Aged

<u>Specimen Code</u>	<u>Orientation</u>	<u>Temp. °F</u>	<u>Ultimate Strength ksi</u>	<u>0.2% Offset Yield Strength, ksi</u>	<u>Elong. %</u>
<u>Smooth Specimens</u>					
IN3LS1	Long.	R. T.	204	176.5	20.5
IN3TS1	Trans.	R. T.	198.5	168.0	21.0
IN3LS2	Long.	800	174.2	156.0	19.3
IN3TS2	Trans.	800	169.0	150.0	17.5
IN3LS3	Long.	1000	169.3	150.2	18.0
IN3TS3	Trans.	1000	163.0	148.8	19.0
IN3LS4	Long.	1200	157.0	143.3	6.5
IN3TS4	Trans.	1200	152.5	134.5	7.5
<u>Edge-Notched Specimens</u>					
IN3LN1	Long.	R. T.	196.6		
IN3TN1	Trans.	R. T.	195.6		
IN3LN2	Long.	800	167.5		
IN3TN2	Trans.	800	160.0		
IN3LN3	Long.	1000	166.5		
IN3TN3	Trans.	1000	159.5		
IN3LN4	Long.	1200	148.4		
IN3TN4	Trans.	1200	151.9		

TABLE XIII

Summary of Test Results from Smooth Specimens of Inconel 718 -
Annealed at 1950°F and Aged

Specimen Code	Orientation	Temp. °F	Stress ksi	Rupture Time hours	Elong. %	Minimum Creep Rate, %/hr.
IN3LS12	Long.	800	170	0 ^a	7.5	
IN3LS11	"	"	165	>4342.6		0.000035
IN3LS15	"	"	160	>1006.3		0.00003
IN3TS13	Trans.	800	165	0 ^a	19.0	
IN3TS11	"	"	160	>4342.4		0.00003
IN3TS15	"	"	155	>1006.3		not measurable
IN3LS9	Long.	1000	160	57.7	5.75	0.0356
IN3LS5	"	"	150	140.4	3.0	0.00618
IN3LS10	"	"	140	710.8	1.5	0.00043
IN3LS14	"	"	135	693.1 ^b		
IN3TS10	Trans.	1000	155	52.5	4.3	0.0218
IN3TS5	"	"	150	58.8	3.0	0.0095
IN3TS9	"	"	140	1142.4	2.0	0.00046
IN3TS14	"	"	135	>1009 ^c	2.0	
IN3LS6	Long.	1200	100	48.8 ^d	3.0	0.0134
IN3LS7	"	"	90	280.3	1.8	0.0022
IN3LS8	"	"	80	697.0 ^d	1.5	0.00068
IN3LS13	"	"	75	913.1 ^d	1.8	
IN3TS6	Trans.	1200	100	32.2	1.8	0.0092
IN3TS7	"	"	90	103.5	2.0	0.00359
IN3TS8	"	"	80	145.1 ^b		0.00028
IN3TS12	"	"	75	1182.8 ^d	1.0	0.000076

a - Fractured on loading

b - Fractured at pin hole

c - Specimen overheated and failed due to controlled malfunction

d - Fractured beneath collar

TABLE XIV

Summary of Test Results from Notched Specimens of Inconel 718 -
Annealed at 1950°F and Aged

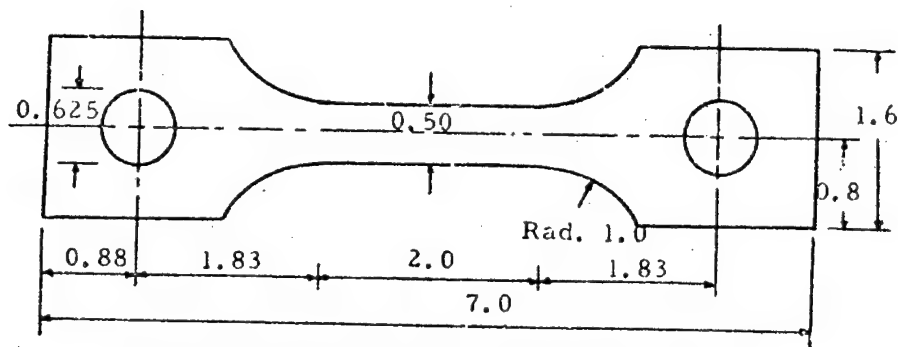
Specimen Code	Stress Concentration Factor, Kt	Temp. °F	Stress ksi	Rupture Time hours
IN3LN25	2.3	1000	150	80.5
IN3LN27	"	"	145	67.3
IN3LN26	"	"	140	267.5
IN3LN28	"	"	130	29.2
IN3LN29	"	"	130	132.1
IN3LN23	2.3	1200	90	5.2 ^a
IN3LN24	"	"	70	45.4 ^a
IN3LN21	"	"	60	384.1
IN3LN22	"	"	50	910.6
IN3LN34	6.0	1000	130	103.6 ^a
IN3LN32	"	"	120	155.5
IN3LN35	"	"	110	197.1
IN3LN37	"	"	100	501.0
IN3LN39	"	"	90	981.5
IN3LN31	6.0	1200	50	40.2
IN3LN36	"	"	45	101.9
IN3LN33	"	"	40	435.3
IN3LN38	"	"	36	2408.1

a - Fractured at pin hole

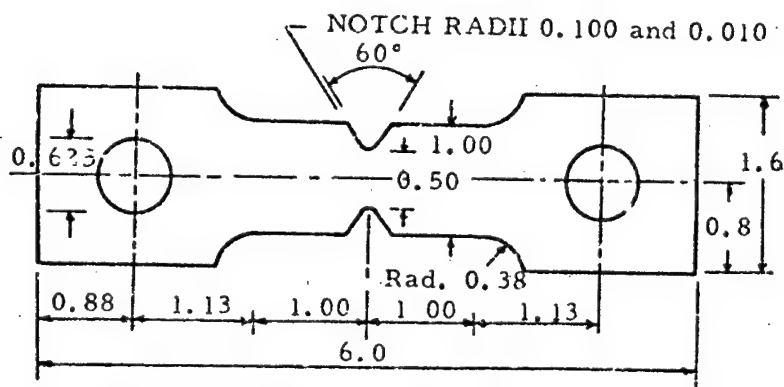
TABLE XV

Summary of Test Results from Sharp Edge-Notched Specimens of
Inconel 718 - Annealed at 1950°F and Aged

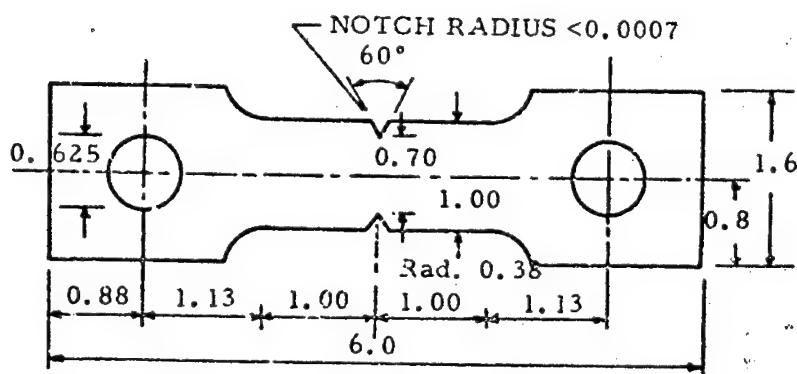
Specimen Code	Orientation	Temp. °F	Stress ksi	Rupture Time hours
IN3LN14	Long.	800	160	502.2
IN3LN15	"	"	155	1078.9
IN3LN18	"	"	150	2856.4
IN3TN15	Trans.	800	157	1572.5
IN3TN13	"	"	155	1656.9
IN3TN14	"	"	150	1426.9
IN3LN5	Long.	1000	100	75.4
IN3LN6	"	"	90	56.1
IN3LN9	"	"	80	98.7
IN3LN12	"	"	75	333.5
IN3LN13	"	"	70	640.8
IN3LN17	"	"	65	500.8
IN3TN5	Trans.	1000	100	134.5
IN3TN6	"	"	90	213.8
IN3TN10	"	"	80	590.1
IN3TN12	"	"	75	1630.9
IN3LN8	Long.	1200	70	4.3
IN3LN7	"	"	60	6.5
IN3LN10	"	"	50	16.1
IN3LN11	"	"	40	8.5
IN3LN16	"	"	30	1771.3
IN3TN8	Trans.	1200	70	2.5
IN3TN7	"	"	60	2.7
IN3TN9	"	"	50	60.5
IN3TN11	"	"	40	2088.6



1a. Smooth (unnotched) specimen ($K_t = 1.0$).



1b. Notched specimen for $K_t = 2.3$ and 6.0.



1c. ASTM sharp edge-notched specimen ($K_t > 20$).

Figure 1. Types of test specimens (all dimensions in inches).

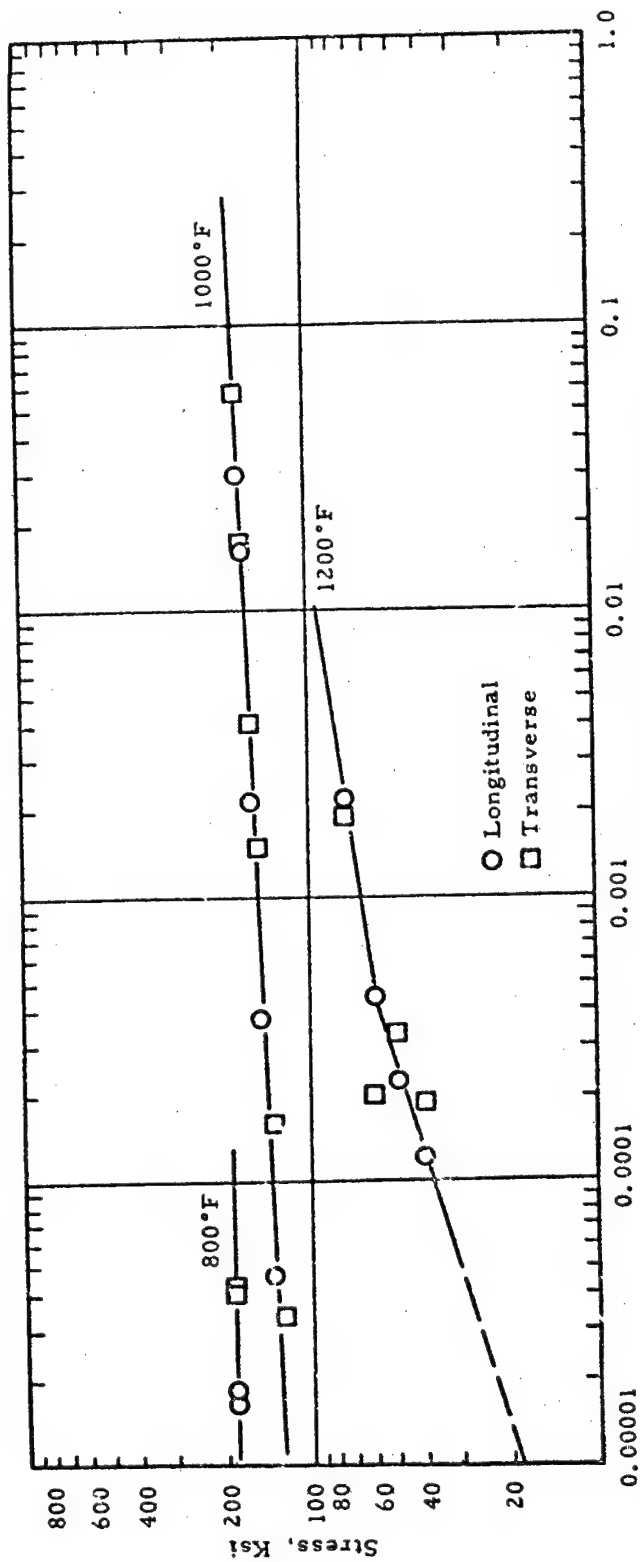


Figure 2. Stress versus minimum creep rate behavior of Inconel 718 in the cold worked and aged condition.

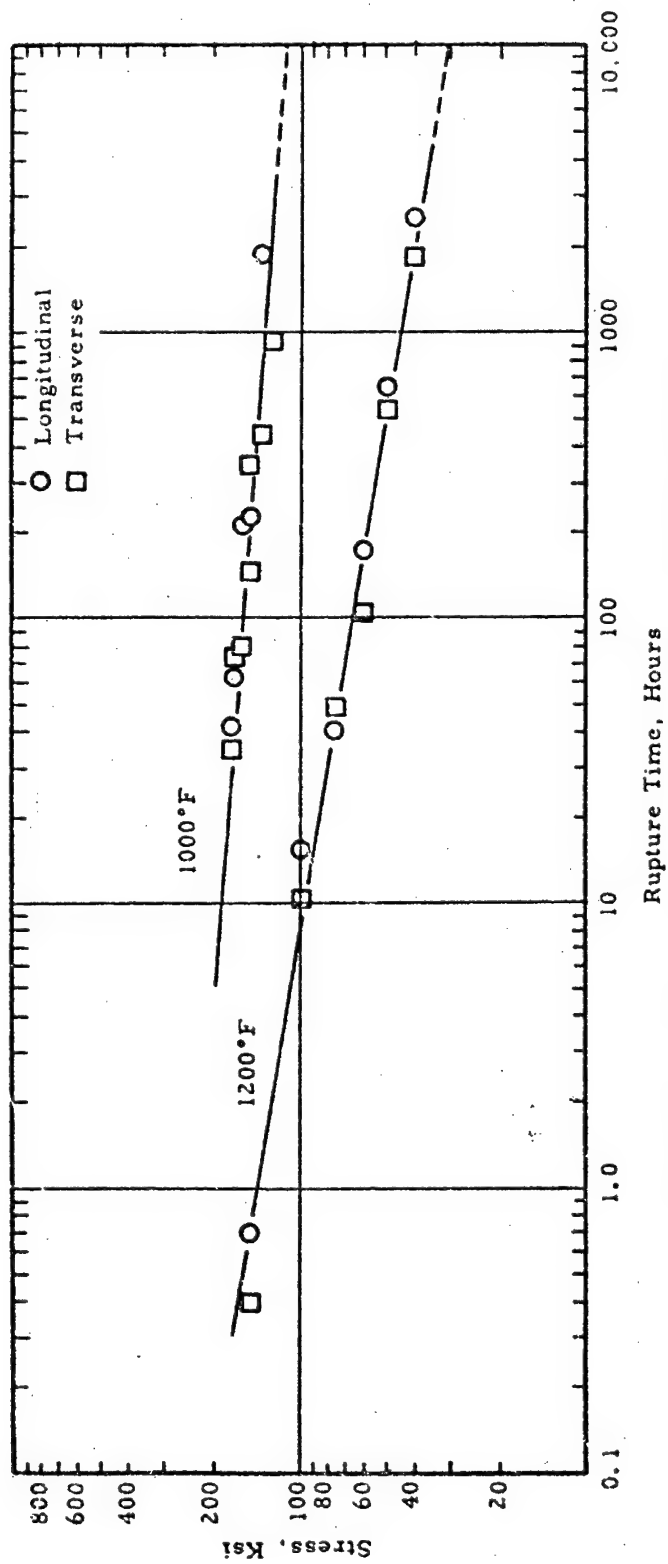


Figure 3. Stress-rupture time curves from smooth specimens of Inconel 718 in the cold worked and aged condition.

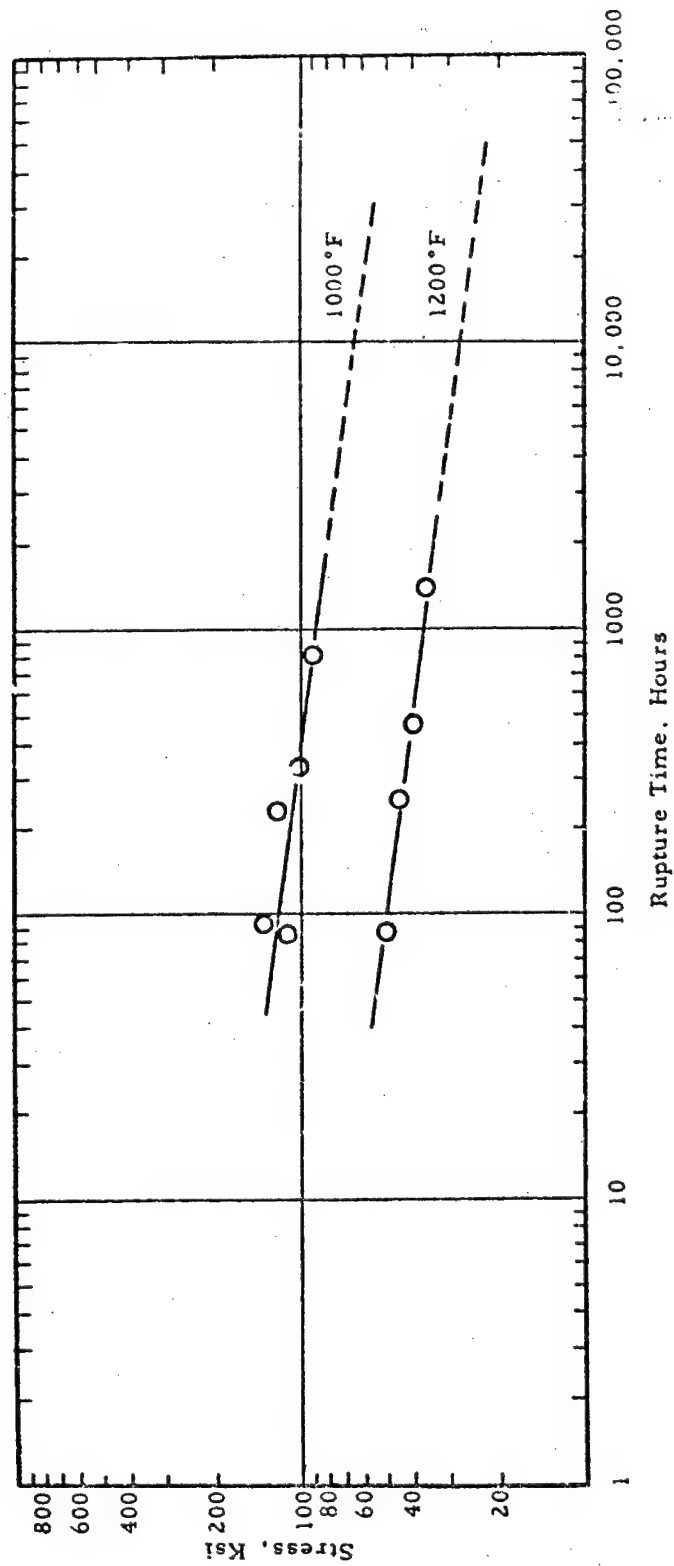


Figure 4. Stress-rupture time curves from edge-notched specimens ($K_t = 6.0$) of Inconel 718 in the cold worked and aged condition.

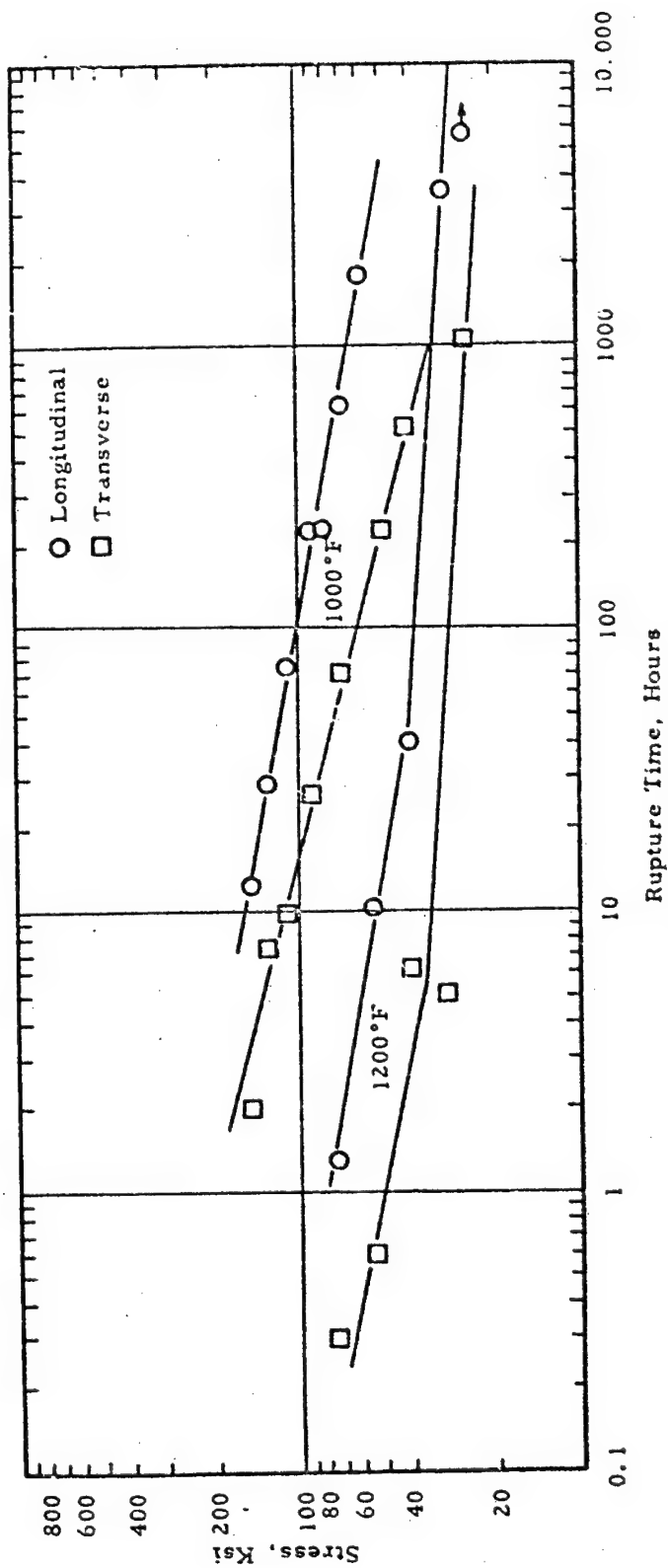


Figure 5. Stress versus rupture time behavior of ASTM sharp edge-notched specimens of Inconel 713 in the cold worked and aged condition.

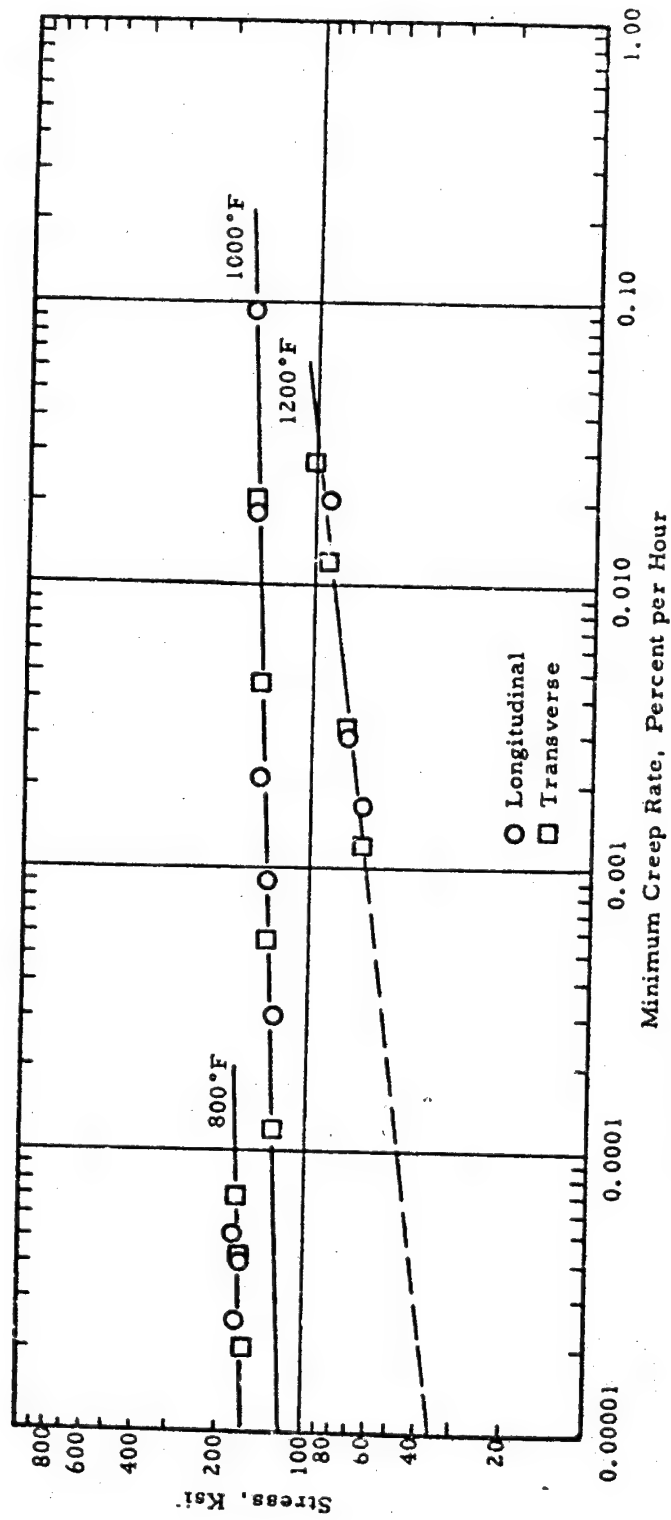


Figure 6. Stress versus minimum creep rate behavior of Inconel 718 annealed at 1750°F and aged.

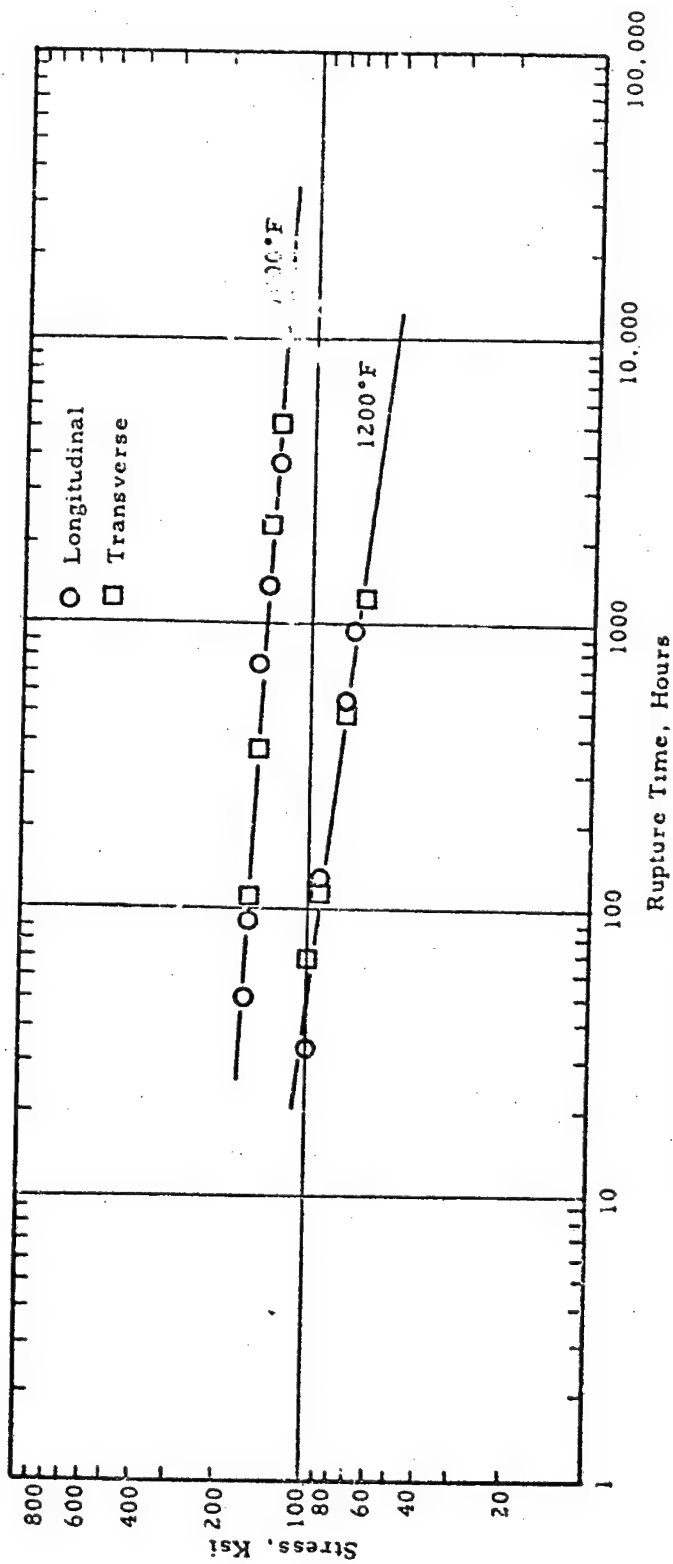


Figure 7. Stress-rupture time behavior of smooth specimens of Inconel 718 annealed at 1750°F and aged.

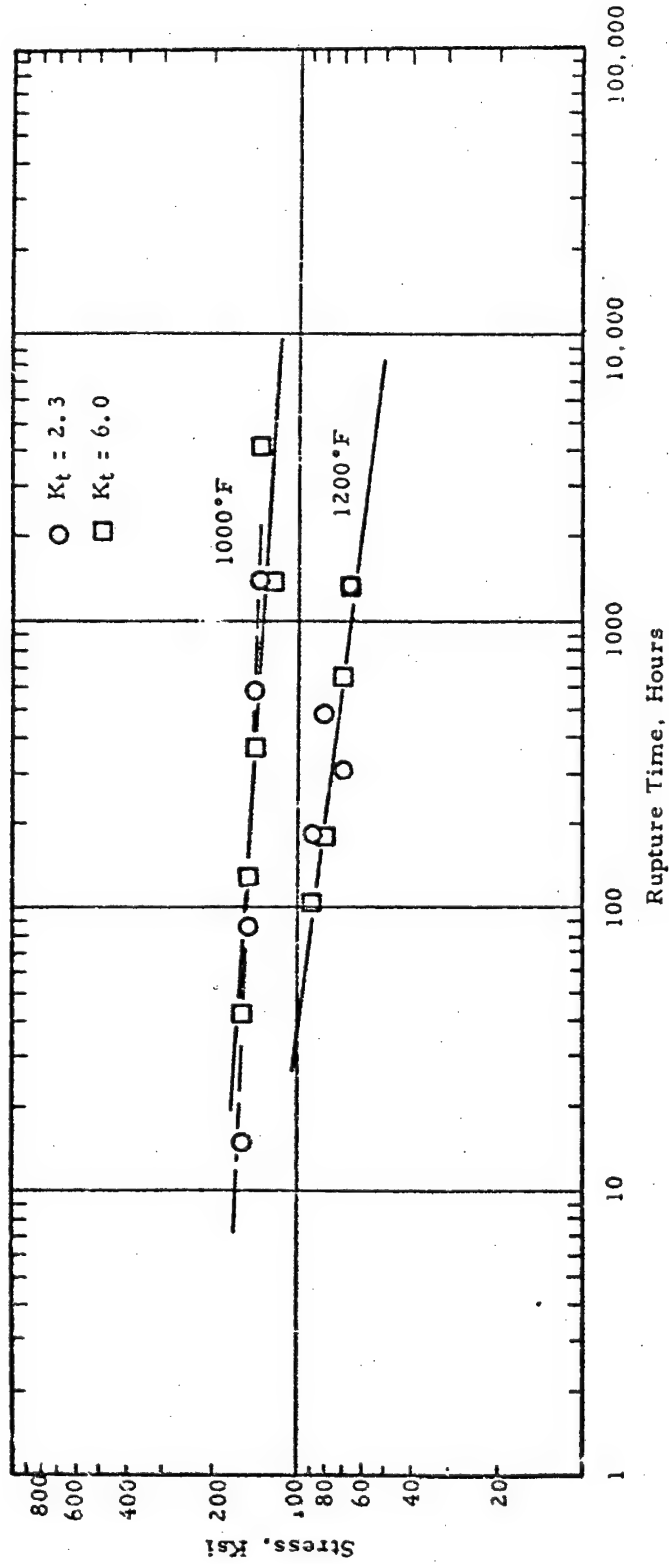


Figure 8. Stress-rupture time curves from edge-notched specimens (notch acuities of 2.3 and 6.0) of Inconel 718 annealed at 1750°F and aged.

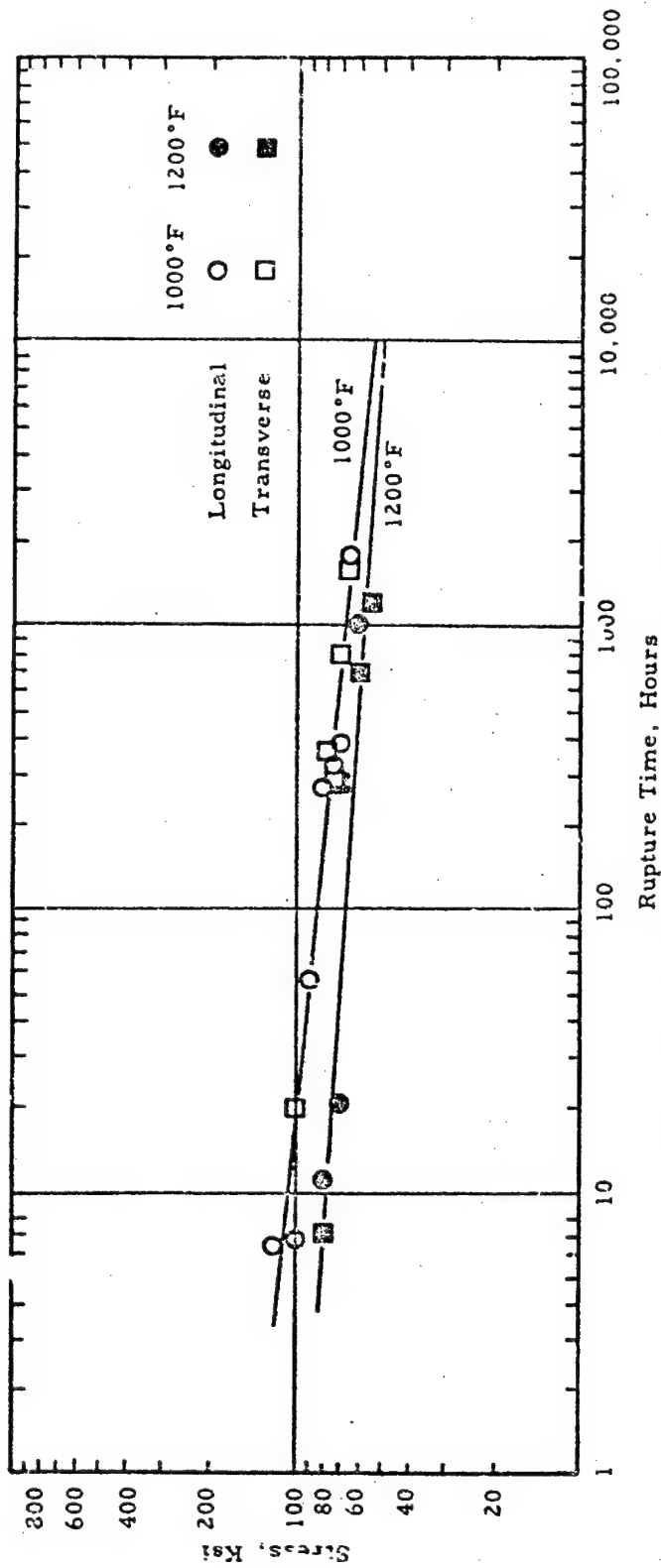


Figure 9. Stress versus rupture time behavior of sharp edge-notched specimens of Inconel 718 annealed at 1750°F and aged.

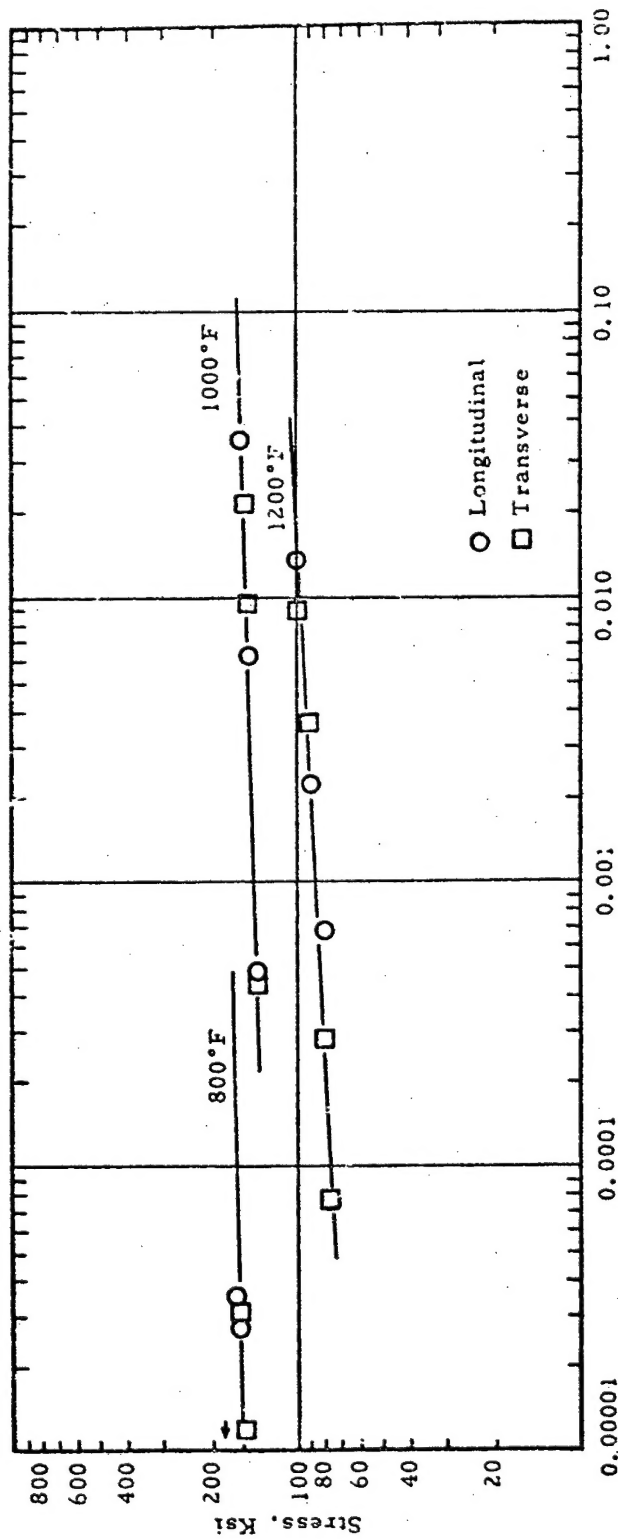


Figure 10. Stress versus minimum creep rate behavior of Inconel 718 annealed at 1950°F and aged.

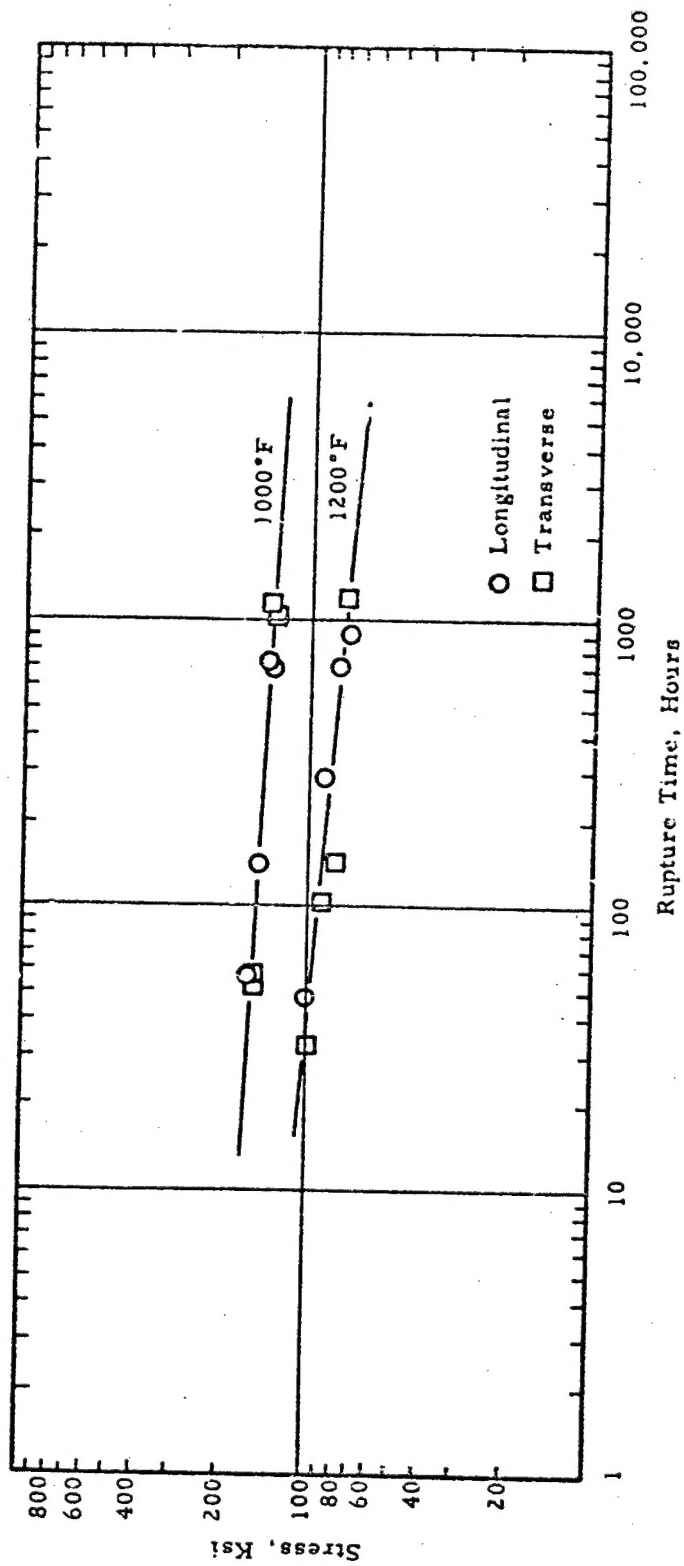


Figure 11. Stress-rupture time curves from smooth specimens of Inconel 718 annealed at 1950°F and aged.

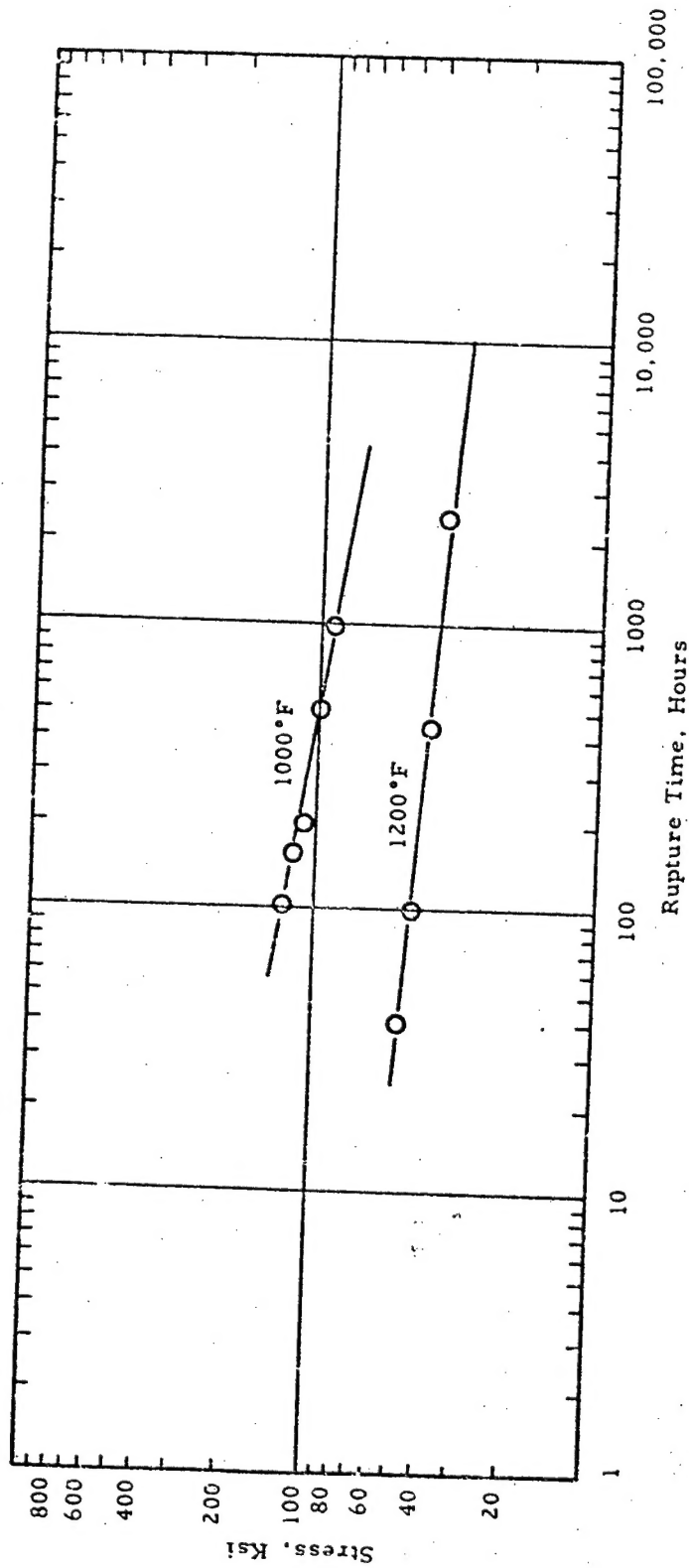


Figure 12. Stress versus rupture time curves from edge-notched specimens ($K_t = 6.0$) of Inconel 718 alloy annealed at 1950°F and aged.

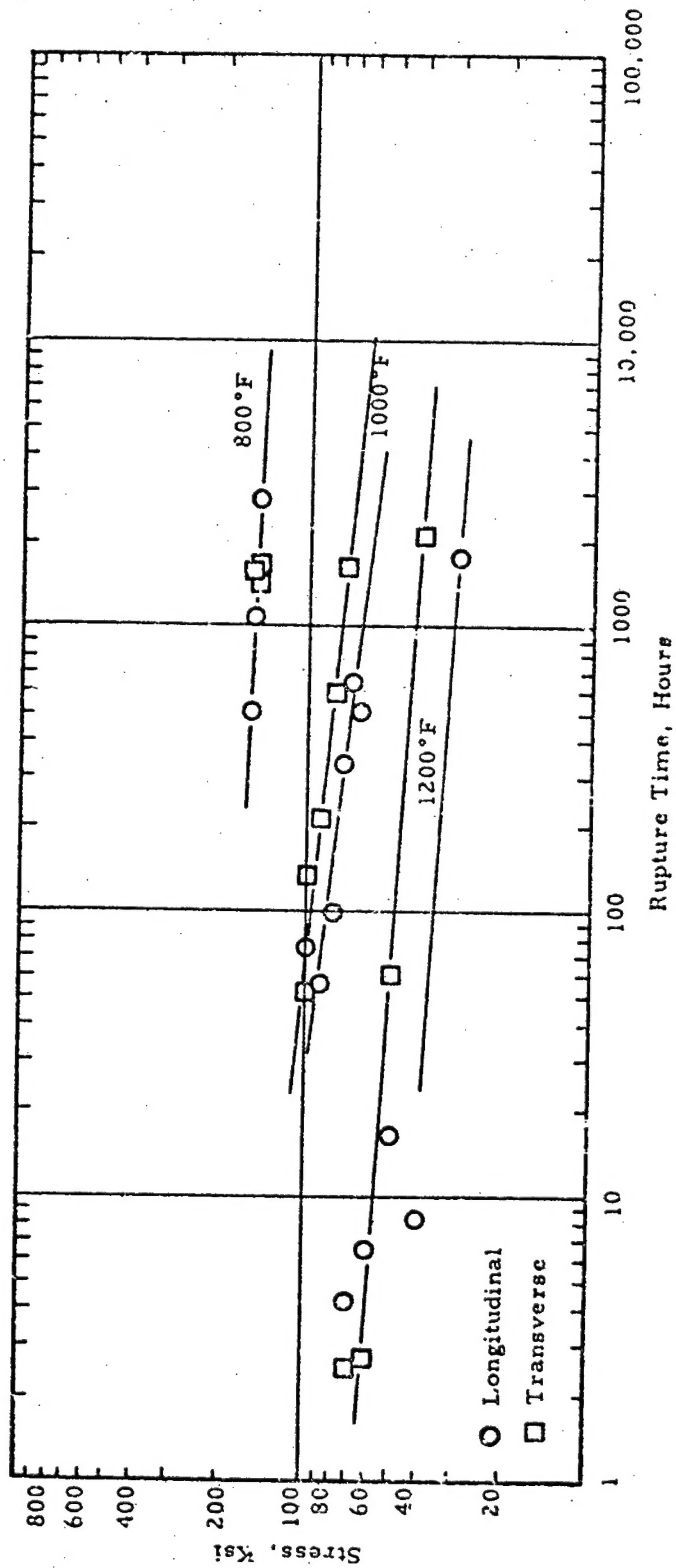


Figure 13. Stress-rupture time behavior of sharp edge-notched specimens of Inconel 718 which were annealed at 1950°F and aged.